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Game Theoretic Modeling of the International Relations System

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Declaration

I hereby declare that I wrote this dissertation thesis by myself in order to fulfill the requirements of obtaining Doctor of Philosophy degree from the Charles University in Prague and that I cited all the literature I have used during this process.

Prague
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Abstrakt

Disertační práce usiluje o modelování systému mezinárodních vztahů. Základní výzkumní otázka se snaží zjistit jaké důsledky pro úspěch jednotlivých strategií a pro kooperaci samotnou mají různá nastavení proměnných a vlastnosti systému jako takové. Práce obsahuje dvě prvky charakteristické pro mezinárodní vztahy, a které nemožno najít v jiných modelech: (i) determinace výskytu interakcí pomocí vzdálenosti a síly; a (ii) vznik (ne)důvěry na základě předchozích interakcí. Model stojí na třech pilířích: agentech, prostředí a pravidlech. Hráči se nacházejí v Hobbesovském prostředí vězňova dilematu tak jak je chápáno realisty. Změna výplat reprezentující vnik (ne)důvěry však umožňuje formalizaci teze konstruktivistů o různých podobách anarchie a o vzájemně konstitutivním vztahu struktury a aktérů. Multiagentní počítačové simulace jako metoda zasazená do rámce abduktivního uvažování a sloužící ke generaci dat se stala nutnou vzhledem k chybějící různorodosti empirických informací a nemožnosti experimentů v reálním světě. Zdrojový kód napsán v jazyce C# obsahuje 62 strategií použitých Axelrodem, ke kterým jsem přidal několik dalších potenciálně úspěšných pravidel společně se třemi novými strategiemi odpovídajícím běžnému chování států. S cílem dosáhnou robustnosti výsledků byla aplikace při různých nastaveních (včetně úrovně nejistoty a rychlosti změny výplat) spouštěna opakovaně vždy s 10 000 iteracemi.

Co se týče strukturálních vlastností systému, ani moc ani vzdálenost neměli vliv na úspěch strategií. Výrazní dopad měla jedině změna výplat. Na úrovni aktérů se prokázal silný vztah mezi průměrným počtem vzájemně kooperativních interakcí a celkovými zisky. Všech pět nejúspěšnějších strategií bylo vysoce velkorysých. Tyto vítězné pravidla pak dosáhli nejvyšších výplat i v kontrolních simulacích, kde měli ostatní aktéři náhodně přidělené pravděpodobnosti spolupráce po každém ze čtyř možných výsledků vězňova dilematu. Nová strategie rovnováhy hrozeb však zvítězila s velkým předstihem. Průměrná úroveň spolupráce tu už nekorelovala s celkovými zisky, no kooperující hráči k sobě stále dokázali najít cestu. Tyto výsledky tak ukazují, že vlastnosti systému vedou politické aktéry ke kooperativnímu jednání. Usilujíc o dosažení nejlepšího vysvětlení, za předpokladu správnosti daného modelu se zdá, že velkorysá spolupráce není jen pomíjivým náhodným fenoménem. Rovnováha hrozeb se ukazuje jako nejlepší způsob jak čelit heterogennímu prostředí a příčiny války by se spíše měli hledat na úrovni interakcí mezi státy. Válka tady tedy není díky systému.

Klíčová slova: Vězňovo dilema, multiagentní simulace, konstruktivismus, vzdálenost, moc, spolupráce, rovnováha hrozeb

Abstract

The thesis models interactions in the system of states. Fundamental research question asked what consequences for success of strategies and prospects of cooperative behavior have particular settings and properties of the system. Thesis includes two features peculiar to international relations that did not appear anywhere else before: (i) determination of interaction occurrence with help of distance and power; and (ii) emergence of (dis)trust out of the previous interactions. The model is based on three elements: agents, environment, and rules. Players interacted in the Hobbesian Prisoner's Dilemma environment as described by realists, but thanks to payoff shift representing emergence of (dis)trust I also formalized constructivist argument of different cultures of anarchy and of mutually constitutive agent-structure relationship. Multi-agent computer simulations set within the abductive reasoning framework were chosen because lack of heterogeneous enough data and impossibility of experiments made this data generating method a necessity. The source code is written in C#. I translated 62 Axelrod's behavioral rules and then added several others that seemed promising. Three new strategies mirroring usual behavior of states were proposed too. To secure robustness of the results, application was run hundreds of times under different settings (including variable uncertainty and shift speed) and always for 10 000 iterations.

As regards structural variables, neither power nor distance changed overall ranking of strategies. It was only payoff shift that wielded significant influence. Strong relationship at the level of actors appeared between overall gains received and average number of mutual cooperations. All five most successful rules were highly generous. These victorious strategies achieved the highest payoffs even in control simulations, where other actors had randomly assigned cooperation probability after four possible outcomes of the game. But the new balance of threat strategy surprisingly won by a large margin. Average level of cooperativeness was no longer correlated with overall gains here, but cooperators still found their way to each other. To sum it up, it seems that properties of the system lead political actors towards cooperative behavior. Using inference to the best explanation, if the model is right, then generous cooperation is not a passing occasional phenomenon, balancing against threats is the best way how to cope with heterogeneous environment, and for causes of war one should rather look at the level of states' interactions. Simply, the war is not here because of the system.

Keywords: Prisoner's Dilemma, Multi-Agent Simulations, Constructivism, Distance, Power, Cooperation, Balance of Threat

Content

1. Introduction

After promising beginning in the early 80s, game-theoretic research program dealing with evolution of cooperation in the international relations remains virtually stagnant since the very end of the 90s onwards. Reasons are abundant. From the increasing prevalence of constructivism after the end of the Cold war, to the relative gains dead end of the debate between rationalist theories. However, it was also the inability to properly and realistically formalize key features of the international relations system that caused gradual decrease of interest in modeling the emergence of cooperation. Of course, formal models, game theory, and mathematics are anything but absent in (American) political science and in the field of international relations in particular. If we consider the huge impact of game theory on such diverse areas of human knowledge as economics, political science, anthropology, biology, and sociology, then the hopes that game theory raised as a potential bridge between various disciplines must have at least some plausibility. But that doesn't say much about the extent to which the computer simulations are associated with formal models build with help of game theory.

To begin with, for reasons of clarity I must clearly distinguish complex systems, agent-based models, and multi-agent simulations. Differences between them are not settled even in the scholarly literature so you can easily find expressions like complexity theory, agent-based simulations, or multi-agent systems. From now on I will, however, use *complex systems* only as a description of real world phenomena, *agent-based models* as their theoretical simplifications, and *multi-agent simulations* as a method of data acquisition. Agent-based models and related multi-agent computer simulations are widely used in natural as well as social sciences. They enable us to better understand and/or improve the functioning of anything from air traffic to human social networks. When connected with game theory, they serve as a powerful tool for solving such complicated problems as that of human cooperation or the spread of particular genes in animal populations. Thus there is no wonder that anthropology and evolutionary biology are leading fields in the research concerned with application of game theory upon complex systems via computer simulations.

My goal in this thesis, however, is to show that computer simulations, game theory, and especially agent-based modeling of complex systems are some of the most promising venues, where the scientific attention should be directed in political science. This being especially so if we try to understand the functioning of the international relations system and to link the insights from different theories. The system we are concerned here with is a perfect example of complex system as I will show later in the thesis, and agent-based modeling not only takes advantage of rationalist individualism, but also shares many common points with constructivism while simultaneously trying to bridge the quantitative-qualitative division in methodology.

When studying interactions of states scholars don't have empirical data comparable in any meaningful way with those of other disciplines. While natural laws follow the same path for billions of years and available empirical evidence of how human societies worked goes for thousands and thousands years back, international relations system as we know it is not older than few hundred years. There are usually thousands of individual members of any particular species and you can pick up any of the numerous human societies and then compare them as wholes if necessary or potentially promising. But there are just about 200 sovereign states (much fewer previously) and they constitute only the single one system of international relations. Even if we consider the last 5 thousand years of human political history, so not restricting ourselves to the present system of sovereign states, data would not improve very much. Besides obligatory references to Thucydides and maybe few other writers, statesmen, or events, there are not many inferences about international politics drawn from distant past that could not be drawn in the same way from history of Europe in the 17th century. Possibility to generalize from isolated states, or system(s) of states, before the Age of Discoveries upon the closed world of current international relations system is similarly doubtful. At the same time the system is clearly changing despite its relatively short history, and it is not only the consequence of technology. Individual actors cooperate much more than in the past. In order to explain any changes in the system, we must either imply from the few data we have (which need not to be necessarily a wrong choice) or we need to acquire data in some other way.

Agent-based modeling of the complex systems like that of international relations, where agents are supposed to be states, suits the task of generating data perfectly. It would enable us to examine the consequences that given environment constructed in order to mirror properties of the international system would have upon interactions of actors (states). That is the reason for using the method of computer simulation. Namely, acquiring sufficient data that empirical world is unable to supply because of impossibility of experiments, small number of states, N = 1 problem related to the number of alternative systems, and relatively limited time span of available data. For example, if I had intended to inquire into the causes of war, I could have easily used some statistical data on occurrence of conflicts. After all, wars are plentiful. But this is not the case if the goal is to inquire into the consequences of the system. War might simply be just one such consequence among many others and possibly even only under some specific circumstances. We cannot know whether it is so unless we examine the system. If one tries to test the claim that it is the systemic level that must be looked at for the causes of war, then it is basically unavoidable to model the system, isolate key variables, and use all possible combinations of parameters. I tried to do precisely that.

However, before accepting the data and proceeding to their analysis we first need to construct a convincing model of the international relations system. This seems to be the greatest challenge. Not only that proponents of rationalist theories understand the system differently than let's say constructivists, but even understanding within these broad groups can differ a lot. Theoretical single-mindedness with respect to model construction risks rejection from proponents of competing theory and/or accusation of dogmatism. Combining insights from various theories on the other hand hinders examining of any theory individually and almost certainly invites the label of eclecticism. Yet since modeling enterprise is not a beauty contest of available theories, it appears to me more important to balance out parsimony with sufficient attention to details, rather than paying too much attention to theoretical purity. Model should be both intuitively realistic in nature (thus not overlooking some significant feature of the system), and it should also stay faithful to the well-known modeling principle of keeping it simple.

I will hopefully fulfill these criteria in my thesis. The model is based on three elements (agents, environment, and rules) that are shared by both agent-based models, and constructivist theory. Anarchic environment of the international relations system is understood in realist terms of Hobbesian state of nature, in which interactions of states correspond to game-theoretic concept known as the Prisoner's Dilemma. At the same time I, nevertheless, recognize the fact that meaning given to anarchy can vary. After all, we can see some difference when we compare relations of the Great Britain and the United States on the one hand, and Israel and Iran on the other. Or to stay within the realm of broadly defined Central Europe, it is not the same story when one talks about relations between let's say Serbia and Croatia, or alternatively between Serbia and Slovakia. Prevailing uncertainty about other actor's future behavior can shift either towards close friendship or fierce enmity. I enabled emergence of (dis)trust among states in form of reward shift based upon previous interactions, and thus in a way formalized the constructivist argument of mutually constitutive relation of structure and agents. Moreover, states that are closer to each other on the square lattice and also those more powerful ones interact repeatedly with higher probability. That ought to mirror spatial and power-based character of the world politics. Or do you think that Saint Kitts and Nevis can have any interests in having an embassy in Slovakia?

With respect to individual players, it is possible to formalize gradual transition between two common options in the Prisoner's Dilemma, but I restrict available choices of states to simple cooperation and defection. When trying to achieve heterogeneity of players' behavioral rules in their pairwise repeated interactions, I reached for Axelrod's 62 strategies used in his second tournament. Few other rules successful in different models were added as well together with three completely new strategies designed according to common behavior of states in the international relations system (balancing against threats, bandwagoning, and balancing against power). Finally, no learning, no strategy drift, no ecological or evolutionary mechanism was included in the model, but I added both kinds of noise instead. Unlike in biology or among humans, presence of progress in international relations is dubious, to say the least, while uncertainty is omnipresent. I believe this combination of parameters might be a fair compromise that satisfies the need for simplicity while keeping the model realistic enough.

But what is the point of such a research, if Axelrod had already shown the possibility of cooperation among egoists? Added value of this thesis will be first and foremost the fact that I model the system. Axelrod didn't run his tournament with the specific idea of international relations system in mind. His findings were only later applied upon anarchical environment of sovereign states and some of his assumptions were thus criticized as unrealistic. Furthermore, even if simulations that followed after Axelrod's pioneering tournaments included several features present also in my thesis, their combination in this model is unique. What is even more important is the fact that at least two things peculiar to functioning of international relations have to my best knowledge not appeared anywhere else in a similar form. These are (i) determination of interaction occurrence with help of distance and power position of actors, and (ii) emergence of (dis)trust that formalizes mutual influence of agents and structure via reward payoff shift. Added value of the model is also represented by its effort to examine validity and robustness of Axelrod's results, which is made possible by using the original set of 62 strategies. Last but not least, an attempt to reconcile constructivism with rationalism via agent-based modeling merits certain attention probably on its own.

In order to analyze and correctly interpret behavior of states and their interactions we need to better understand how the system of states works. Yet we can see everyday that states do actually cooperate among themselves so what new can the model bring about? The thing we don't know is whether cooperative behavior is merely one of many potentially prosperous paths of behavior, or if it is the most successful one from all other possible. Is the cooperation in the North Atlantic region only a matter of chance, or naturally occurring phenomenon? The basic research question therefore asks, if properties of the international system enable and facilitate success of cooperative behavior, or alternatively if such a success is just a matter of chance? Simply stated, what is the best way how to face anarchy? If it is cooperation, then what kinds of cooperative strategies are the most successful and under what conditions? Is it better to disregard occasional lies of communist North Korea, or rather to retaliate immediately? And does it depend upon particular contexts? I am not that much concerned about who precisely will win the simulations, as with the issue if top scoring rules will be ready to defect first (i.e. if they are nice or mean). They might be generous and thus willing to return more cooperation than received, or unforgiving and thus not willing to cooperate again after opponent's defection. There are provocable strategies that retaliate immediately and others that are slow to reply. These are the basic questions I would like to find answers to in this thesis.

Except for introduction and conclusion, the text is divided into four chapters. The following one offers a review of literature on evolution of cooperation by direct reciprocity mechanism in the two persons Prisoner's Dilemma game. It is subdivided into the first part dealing with mathematical analysis and the second one devoted to various agent-based models. After that comes the core chapter describing the whole model of the international relations system in a hopefully accessible manner. Its three subchapters deal with agents, environment, and finally rules that represent connection between the former two elements. Third chapter pays close attention to abductively oriented methodology and the way how individual strategies and variables of the model were operationalized in the source code. This chapter is in later parts rather technical and can be harder to grasp for readers unfamiliar with C# or Fortran. Finally the fourth chapter presents results of simulations and their basic statistical analysis. All data as well as the source code of the program can be found on DVDs attached to the thesis.

2. Review of Literature

The Prisoner's Dilemma became in the second half of the 20th century a common tool for analyzing many social situations, in which individually rational behavior led to collectively suboptimal outcomes. This happened also thanks to successful spread of game theory from economics to other (not only) social sciences. In the field of international relations this non-cooperative game often serves as a metaphor describing arms races, or the security dilemma itself in an anarchic environment, where self-help of states prevails (see Brams - Davis - Straffin, 1979; Snyder, 1971; Jervis, 1982; Taylor, 1987). Usually it is accompanied by a short story about two suspects detained because of the burglary. They are interrogated, but the police have enough evidence for the prosecutor and the court only to sentence them from some minor charges. Thus they are offered separately the following proposal: "If you confess to the burglary, I can spend a few words in your behalf in front of the judge, so that you would get lower sentence for helping us to solve this case, and you would get out the prison really soon. But if you don't confess, I have still enough evidence to send you to the prison for several years for minor charges. Try to think about that." Naturally, both suspects confess and they suffer many years of solitary confinement since no one can claim the credit on its own for helping the police to solve the case.

The logic of this situation can be represented by the following figure, where two players can choose between cooperation (C) and defection (D) giving thus rise to four possible end states (2x2) with attached payoffs. These are temptation (T) for unilateral defections, reward (R) for mutual cooperation, punishment (P) for mutual defection, and being sucker (S) for unilateral cooperation.

		Player B	
		Cooperate	Defect
Player A	Cooperate	R, R	S, T
	Defect	T, S	P, P

Figure 1: Payoff matrix

For game to be considered as an example of the Prisoner's Dilemma, its payoffs must be ordered in the following manner: T > R > P > S. Moreover, in order to secure that mutual cooperation is really collectively optimal solution and thus better than alternating unilateral cooperation and defection, it is also necessary that $2R > T + S$. In any game that fulfills these conditions, it is better for both actors individually to defect irrespective of other player's decision.

Real world examples of a decision between high and low tariff levels, or between increasing arms spending and its alternative of disarmament, correspond to this logic. Individually rational behavior (arming), however, leads to the Pareto suboptimal payoff as a result of mutual defection (arms race), which is the only Nash equilibrium of the game. That means that even though no player can improve its own position and therefore increase the payoff received by simply changing only its own decision (Nash equilibrium), there still exists another outcome that can make at least one player better off without decreasing the payoff of another (Pareto efficiency). The dilemma then rests in the fact that there is another collectively more promising outcome, that of mutual cooperation, which can provide higher payoffs for both players. "Whenever you observe individuals in a conflict that hurts all of them, your first thought should be of the Prisoner's Dilemma" (Rasmussen, 1989: 29). Question of how to get to that outcome, and thus how to achieve corresponding payoff, is the key problem of this chapter.

Enormous spread of game theory and wide application of the Prisoner's Dilemma caused huge number of articles and other publications from various fields of study dealing with the problem of cooperation. Great deal of them is, nevertheless, not older than 30 years since the whole research program in fact began only after influential articles by Robert Axelrod (1980a, 1980b) in which he offered results of two computer tournaments of many different strategies competing in the repeated Prisoner's Dilemma. Not much of the literature published before the 1980s is relevant with respect to the later development of the research program (exceptions include Trivers, 1971 and Maynard Smith – Price, 1973). Yet the problem of cooperation emergence and of multi-agent simulations as a research method dealing with agent-based models of complex systems gave rise to several special issues and review articles during the last 30 years. Besides usual review articles summarizing specific periods of intense research (Axelrod – Dion, 1988; Hoffmann, 2000; Gotts – Polhill – Law, 2003) one can also find many studies focused on specific fields like sociology (Macy – Willer, 2002), anthropology (Fehr – Fischbacher, 2003), or biology (Doebeli – Hauert, 2005).

One of the effects of wide interest in the Prisoner's Dilemma and resulting overlap of individual disciplines is that many sources referred to in this review of literature are not primarily concerned with international relations. This tendency is further strengthened by the fact that the emphasis in research on evolution of cooperation in the Prisoner's Dilemma has shifted from political science towards biology and anthropology. Although the research program as such was actually launched by political scientist Robert Axelrod, the end of the era of strong interest in this problem within the political science is marked by the article that won Heinz Eulau Award in late 1990s (Bendor - Swistak, 1997). In that paper authors summed up, clarified, and basically also solved the whole debate about various kinds of stability in non-cooperative games. The second effect of rapid growth of literature on the topic of Prisoner's Dilemma is the need to limit the scope and increase the focus of any future review. I tried to set those limits in this chapter in such a way that they will include everything that is useful and practical from the international relations point of view.

For example we know several alternative mechanisms that can lead to emergence and stabilization of (mutual) cooperation (Nowak, 2006), but only few of them are applicable upon interactions of states. Kin selection as a mechanism explaining cooperation is of no use for us and similarly for the indirect reciprocity that requires reputation in order to determine who is willing to cooperate with whom. Not that the reputation had no place in international relations. On the contrary, under certain circumstances it can even facilitate emergence of some kind of social norms. But the necessary assumptions of indirect reciprocity that there are no repetitions of interactions and that states with their leaders expect costs of cooperation to be returned not by those they cooperated with, but by some other third party, are not exactly part of the most easily generalizable image of reality.

The case of group selection is not very different. According to this mechanism players should altruistically sacrifice part of their own gains in order to enhance the ability of group to survive when compared with other groups. While at the higher (between groups) level this is clearly an example of competition among groups, at the lower (within group) level of this mechanism we are basically speaking about *collective action* problem in the Prisoner's Dilemma with more than 2 players, where free riders outcompete altruists. At the first sight it seems that this mechanism might have been able to explain origin, functioning and competition of alliances of states. But before speaking of the group selection, we must first prove that competing groups/alliances embody different cultures and different functioning, and that these represent (dis)advantage in comparison with competition. It also must be shown that formation or at least continuation of alliance is more than just a result of self-interested behavior of its members. As one of the few suitable examples we can think of is the North Atlantic Treaty Organization after the Cold War but even here any competition from the other groups is absent. To explain the Cold War itself we can, furthermore, reach for much simpler theories than is the group selection. Besides that, security dilemma at the level of binary interactions better represents international security environment than the metaphors of collective action or common goods.

Remaining mechanisms of direct and network reciprocity are therefore best suited for application upon interactions of states. Drawback of the reciprocity in structured environment (network), where different players interact together with different frequencies, is that research is usually limited to actors with zero memory and interactions with only immediately neighboring players. This in fact corresponds to the single round Prisoner's Dilemma in rather isolated, fragmented environment. Only very few international encounters (if any) can be described as this kind of the Prisoner's Dilemma game. And it is only the structure or rather networked character of interactions that makes cooperation possible. At the same time even the results of simulations that operationalize models based on direct reciprocity depend in great extent upon the way interactions are structured. Thus it is hard to clearly separate the question of who interacts with whom, from the question concerning the mechanism that stands behind the emergence of cooperation. From what was mentioned above it should now be at least partially clear, in what direction would this review of literature proceed.

This chapter tries to offer review of relevant literature on emergence and sustaining of cooperation in the Prisoner's Dilemma But since I am concerned with elementary level of relations among states with the least possible number of additional assumptions, the primary goal of this review of literature is thus the summary of findings concerned with solving of two-player repeated Prisoner's Dilemma via direct reciprocity mechanism. It is important here to remind that the period of intense interest in direct reciprocity is approximately identical with the period when political science dominated the research program on evolution of cooperation. By the 'summary of findings' I more precisely mean emergence and stabilization of cooperation, under what conditions can that happen, and what strategies can lead to it. I will deal with the single-shot Prisoner's Dilemma only marginally and even then only in case of being it important for understanding of the context. The same holds also for other mechanisms of the evolution of cooperation. All the models mentioned in this review assume large number of players. Thus when I speak of two-person Prisoner's Dilemma, I mean that every player of that large number interacts in all its binary interactions with only one other actor. The other way would be the already mentioned collective action problem.

Two basic ways of solving the Prisoner's Dilemma problem determines also the structure of this chapter. Even if the complexity of many agent-based models usually severely limits the application of mathematical analysis, deductive reasoning provided various interesting results I would like to take a look at in the following subchapter. Attention there is mostly dedicated to different understandings of stability of strategies in the Prisoner's Dilemma. Rest of the chapter is devoted to the results obtained by multi-agent simulations. These are influenced by several factors, most important of which are structure of interactions, modifications of payoff matrix, and noise both as an improper implementation of own decisions as well as misinterpretation of opponent's behavior. The chapter is structured accordingly. Many other factors influencing prospects of cooperation in the Prisoner's Dilemma deserve our attention, but their usefulness for any model of the international relations system is negligible. And this chapter should serve precisely as an aid for any attempt to model interactions of states.

2.1. Results of Mathematical Analysis

Because of almost complete lack of game theory education and mathematical methods training (except for statistics) at the university level studies of political science, but also because of my own repeated inability to grasp many (later evidently trivial) proofs and calculations, it is useful to recommend at least some of the books one can use in order to get familiar with basic concepts, solutions and proofs of the game theory. One of the best is still *Game Theory for Political Scientists* (Morrow, 1994) also thanks to its focus on non-cooperative games. Another suitable book for those interested in political science is *Game Theory and Political Theory: An Introduction* (Ordeshook, 1986). Last but not least, Varoufakis with Hargreaves Heap (2004) took a look at game theory from more critical point of view trying to set it into the broader context of social sciences.

As mentioned earlier, in the single-shot Prisoner's Dilemma defection is the only rational solution. Thanks to *backward induction* and *common knowledge of rationality* the same holds also for finite number of iterations. Backward induction says that knowing how the last round will eventually turn out, defection becomes the choice maximizing individual utility of both players also in the penultimate iteration. Going backward we then reach the very first round showing that defection is the only rational behavior even in the finitely repeated Prisoner's Dilemma. This does not hold, if one or both of the actors are not sure about the opponent's rationality. Simply if we cannot be sure about the common knowledge of rationality, which assumes that I know that the opponent knows that I know that (s)he knows that I know etc. ad infinitum that we are both rational, then cooperation is possible even in the game with finite number of repetitions (Kreps – Milgrom – Roberts – Wilson, 1982).

Situation is completely different, if player don't know the number of iterations. This is usually formalized via so called *discount factor* (w) that can be understood also as a probability of occurrence of the next round of interactions. Even though common interpretation in economics does not necessarily relate discounting to any future probabilities, because delayed consumption automatically assumes lower utility compared to the immediate one, in the agent-based modeling it commonly gets this particular additional meaning. Discount factor's values range from 0 to 1, and the closer it is to the latter, the longer is the *shadow of the future* or the prospects of extended encounters. In other words, higher discount factors means higher probability of next round as well as greater importance of future payoffs.

With a sufficiently high w defection ceases to be the best strategy and thus, as Axelrod proved (1981: 309), there is no unbeatable strategy. Under notion of unbeatable strategy one should understand here such a rule, that there is no other strategy able to get higher payoff while interacting with any conceivable opponent. By simple adjustment of several infinite geometric series one comes at the conclusion that if $w > (T - R)/(T - P)$, then neither nice (i.e. one that never defects first) nor mean strategy can be unbeatable. And even if the non-existence of the best strategy seems to be a pessimistic conclusion, in fact it represents an opportunity for cooperation since in the single-shot game the unbeatable strategy was actually defection. Non-existence of the absolutely best strategy, moreover, doesn't mean that there cannot be some, let's say, relatively best strategies. That is, strategies best under certain circumstances, as for example when we know exactly which rules are used by other players in the group/population.

One of the attempts to formalize some less demanding criteria of success than was the unbeatability is so called *collective stability* (Axelrod, 1981). Strategy fulfills this criteria if, under condition that all other players in group also use this strategy, it is able to prevent successful invasion of individual attacking player that uses any other strategy. There is also an important analytical shift since the success of strategy is conditioned by the environment in which it is embedded (notice the adjective *collectively*). Thus if we understand V as the sum of overall gains from repeated interactions, then strategy A is collectively stable, if for any competing strategy B:

(1) $$V(A|A) \geq V(B|A)$$

If the frequency of strategies depend on their success, then the number of actors using strategy A will not decrease since attacking player B cannot achieve higher gains than two actors using prevalent strategy A, when they interact with each other. At the same time it is obvious that all collectively stable strategy is in the Nash equilibrium with itself because unilateral change of behavior (e.g. from defection to cooperation) cannot improve the individual payoffs received.

One of important results of Axelrod's analysis was also the discovery that tit-for-tat strategy (TFT) is under certain conditions collectively stable. This rule, that cooperates in the first round and then repeats the other player's previous move, won both of his computer tournaments and is collectively stable if:

(2) $$w \geq \max\left(\frac{T-R}{R-S}, \frac{T-R}{T-P}\right)$$

The argument assumes that if TFT can resist both always defecting strategy ALLD as well as the one that defects only in one round, then it can resist any mean rule as regards collective stability. Since no nice strategy can get higher payoffs than TFT itself, when interacting with another tit-for-tat player, then TFT must constitute a Nash equilibrium (for detailed proof see Morrow, 1994: 265; or Axelrod, 1981: 311).

However, the problem is that TFT is not the only collectively stable strategy. ALLD is such a strategy as well and even regardless of the discount factor. For example TFT can invade the group using ALLD strategy only if there are more invading TFT actors and if their mutual interactions are somehow structured. In other words, if they interact more often than their relative numbers prescribe. With respect to the relationship between collective stability and the Nash equilibrium as well as to the *folk theorem* that speaks about possibility of any individually rational outcome in sufficiently often repeated game being a Nash equilibrium (see for example Fudenberg – Maskin, 1986), then it is no wonder that by fulfilling certain conditions regarding w there are many more collectively stable strategies including some of the nice ones (Bendor – Swistak, 1997: 291 & 296).

So even though Axelrod (1981) analytically showed that cooperation can be a stable result of the Prisoner's Dilemma under certain conditions even without enforcement of some authority, his concept of collective stability had exactly the opposite problem than the idea of unbeatable strategy. It was too broad. Plus there were other problems connected to it. First of all it enabled so called *neutral drift*. This phenomenon represents accidental change of particular player's strategy, which however leads to no change in received payoffs (therefore 'neutral'). Such a new rule can persist in the population composed of actors using prevailing and collectively stable strategy, even if this newcomer has not to be necessarily collectively stable itself. The threat becomes apparent after still another strategy drifts into the population and by exploiting this neutral drift spreads rapidly. For example always cooperating strategy (ALLC) doesn't correspond to the inequality (1), but it gets the same payoffs from interactions with TFT players as get two TFT players interacting with each other. It is therefore able to survive in such an environment indefinitely without spreading.

Moreover, collective stability was often confused with evolutionary stability proposed by Maynard Smith and Price (1973: 17). They are really similar[1] but they have some very important differences. The basic one is the fact that evolutionary stability is only the subset of collective stability. It means that not every Nash equilibrium is also evolutionary stable. Evolutionary stable strategies are not prone to neutral drift and thus they should be more unusual than those that are only collectively stable. For instance TFT is not evolutionary stable because of the possibility of neutral drift towards more generous rules that forgive certain amount of defections without punishment and thus make the group vulnerable to mean strategies that exploit such generous players that drifts into the group (Selten - Hammerstein, 1984). In fact the existence of neutral drift in case of all deterministic strategies, i.e. those that decides not according to some probability variables, makes the evolutionary stability in this kind of rules impossible at the end (Bendor – Swistak, 1995: 3598).

Boyd and Lorberbaum (1987) tried to prove the same, but their definition of evolutionary stability was again a bit different than the original one. According to them the strategy would be stable only if even in the case of neutral drift it held, that the sum of gains of defending strategy from interactions with any third rule was at least as big as the sum of gains of neutral drift and that third strategy. Under condition of rule's frequency being determined by its success in repeated interactions with other players,

[1] If all members of the group use the strategy A and face the attacking strategy B, then rule A is evolutionary stable only if it fulfills one of the following criteria: either $V(A|A) > V(B|A)$, or if $V(A|A) = V(B|A)$ then also $V(A|B) > V(B|B)$.

there would be no change in relative numbers of players using defending strategy. However, as was later shown (Bendor – Swistak, 1995: 3597) the understanding of evolutionary stability by Boyd and Lorberbaum in fact meant *collective unbeatability* of the strategy A.[2] Their main result then was that there is no deterministic strategy able to fulfill the stated conditions, if it holds for the discount parameter that:

$$(3) \qquad w > \min\left(\frac{\mathrm{P}-\mathrm{S}}{\mathrm{R}-\mathrm{S}}, \frac{\mathrm{T}-\mathrm{R}}{\mathrm{T}-\mathrm{P}}\right)$$

Farrell and Ware (1989) together with Lorberbaum (1994) then extended the proof of impossibility of such version of stability to include also all of the probabilistic rules.

Absence of collective unbeatability is simply the modification of Axelrod's statement about non-existence of the best strategy because: "When two strategies [A and B] interact with each other the same way that they do with themselves [i.e. neutral drift], their relative fitness depends on their interactions with other strategies [C]. Because neither strategy can be best against every possible third strategy [no individual unbeatability], no pure strategy can resist invasion by any combination of strategies." (Boyd – Lorberbaum, 1987: 59). In practical terms this means that both the population using TFT rule as well as that using ALLD strategy can be invaded by coordinated attack of TF2T and STFT rules[3] and that even without any structuring of interactions (Boyd – Lorberbaum, 1987: 59). In contrast to the version by Maynard Smith and Price there must be of course simultaneous attack by two different strategies, but since STFT is a neutral drift from ALLD and TF2T from TFT, then such a scenario becomes highly probable thanks to the ability of neutral drifts to wait for the right moment.

The whole problem of different kinds of stability was very well explained by already mentioned Bendor and Swistak (1995; 1997). They distinguished strong and weak evolutionary stability by identifying the former with original stability as defined by Maynard Smith and Price (1973) and leading to expulsion of attacker from the group, while matching the latter only with the requirement of not increasing frequency of the attacker (difference is in the change of sign in the last inequality of the first footnote from 'greater than' to 'greater than or equal to'). Stability as defined by Boyd

[2] Strategy A is collectively (compare with 'individually') unbeatable, if for all rules B hold that either $V(A|A) > V(B|A)$, or if $V(A|A) = V(B|A)$, then for all strategies C also $V(A|C) \geq V(B|C)$.
[3] TF2T returns defection only after two consecutive defections by the opponent. STFT plays exactly as TFT with the exception that it defects on the very first move.

and Lorberbaum (1987) then necessarily stand for an evolutionary stable strategy under *any* evolutionary process (Bendor – Swistak, 1995: 3598).

But what is the point of the evolutionary stability as a concept, if it is absent both in its strong as well as the weak version? In fact weak evolutionary stable strategies do exist and there are plenty of them, but they are stable only under some evolutionary processes and not under any of them as Boyd and Lorberbaum demanded. For instance under the most common evolutionary mechanism called proportional fitness rule, when the frequencies of strategies change according to the ratio of their gains to the average gains in the group (Taylor – Jonker, 1978; see also Hofbauer – Sigmund, 1998: 67ff), any „nice and retaliatory strategy is a maximally robust evolutionarily stable strategy“ (Bendor – Swistak, 1995: 3600). Their relative frequency necessary for stabilization of strategy in a group against attacks of other strategy (i.e. its robustness) approaches 0.5 as discount factor *w* gets closer to 1. And since TFT strategy is both retaliating and nice, the above stated holds for it as well.

We pointed out certain comparative advantage of nice and retaliating strategies including TFT. Two major problems nevertheless remain. First, application of evolutionary mechanisms even in way of proportional fitness rule is in the field of international relations rather dubious. Even if we understood such a mechanism as a metaphor of imitation or learning, which are usually formalized in a different way, we would still have to face the objection that the ability to learn is rather uncommon and rare in international relations. We can speak of socialization and thus maybe also of taking over of certain strategies, but this happens in much more structured environment (e.g. geographical proximity, distribution of capabilities etc.) than is assumed by results based on proportional fitness rule. Mathematical analysis itself cannot solve this problem. However, it is a perfect case for simulations and agent-based models.

The second major problem of previously mentioned results of mathematical analysis is total absence of even the minimal occurrence of *noise*, when player for example interprets defection as cooperation, or alternatively by accident cooperates instead of defecting (or vice versa). These mistakes either in form of misperception of opponent’s behavior, or in form of misimplementation of own decisions, are common both among people as well as in international relations. Without them we could hardly fully explain the events in the first days after German attack on the Soviet Union, shooting down of Korean airliner above Sakhalin, reasons for going to the second war in Iraq, development of the battle of Dunkirk, or incident in the Gulf of Tonkin.

On some strategies both kinds of noise have basically the same impact. Occurrence of any kind of noise leads two interacting actors using TFT strategy away from mutual cooperation. If the game is sufficiently long, two such players will end up with the average gain per round equal to (T + R + P + S)/4 regardless of the extent of noise (Molander, 1985: 612). Interestingly enough, this average gain per round is same as the average gain per round of two players randomly choosing between cooperation and defection. One way to overcome noise is for example generosity that enables forgiving some defections without punishment. This, however, leads to exploitability by mean strategies. Bendor (1993) analyzed this basic interchange between cooperation and exploitability (Axelrod – Dion, 1988) under condition of both kinds of noise and found out that lower than absolute exploitability is possible only if we accept lower than absolute cooperation. Players trying to avoid exploitation thus must be at least to some extent provocable (they must return defections). But those actors are at the same time prone to be provoked by noise hence causing diminution of payoffs. Yet noise need not to have only the negative consequences. It can also enhance the prospects of cooperation (Bendor – Kramer – Swistak, 1996: 334-335; Bendor, 1993).

We already know that neutral drift renders evolutionary stability in its original form impossible, but Reinhard Selten (1987) came out with a concept of *trembling hand* while doing a research on extensive form of games. Similarly as in the reality this trembling hand principle ensures that there is at least some small probability that player will by accident make any at that time available decision. Any imaginable outcome of the game can thus occur with certain small probability, which makes possible to distinguish behavior of potential neutral drifts (see Selten, 1987: especially 300 & 312). This indirectly enables the existence of evolutionary stability. In order to analyze games with possible mistakes he, therefore, created so called *limit evolutionary stable strategy* that in fact represents the limit of original evolutionary stable strategies in a series of games in which the probability of mistakes gradually approaches 0 (Selten, 1987: 271 & 303). This limit stability constitutes „generalization of the ESS [evolutionary stable strategy] concept to symmetric extensive two-person games“ (Selten, 1987: 271).

Boyd (1989) proved it as well, that mistakes in implementation of decisions allow evolutionary stability, thereby corroborating the possibility of positive effects of noise. The proof is simple and rest on the fact that if strategy is the only best answer in interactions with itself in noisy environment (i.e. no neutral drift), then it is also evolutionary stable under condition that the frequencies of attacking strategies are sufficiently low. Boyd also stated several examples of evolutionary stable rules in such an environment. These include unconditional defection and certain form of Axelrod's winner (contrite tit-for-tat or CTFT proposed by Sugden, 2004: 116-7). Player using CTFT strategy can correct its own mistakes of implementation with help of standing (contrition, content, and provoked) and hence overcome the noise when cooperating with its twin. However, CTFT cannot correct its own mistakes of interpretation.

Others (Boerlijst – Nowak – Sigmund, 1997) showed that evolutionary stable in an environment with mistakes in implementation of decisions can be also the so called Pavlov strategy known under abbreviation WSLS too (see Fudenberg – Maskin, 1990; Kraines – Kraines, 1989). This rule cooperates after mutual defection or mutual cooperation, and defects in other cases. Thus it changes its behavior in a manner similar to Pavlovian reflex after negative stimulus (low payoff) and continues along the current path after positive stimulus (high payoff). During the interactions with another player using the same WSLS strategy this king of reflexivity overcomes both kinds of noise. In an environment with low level of mistakes in implementation of decisions WSLS is for example evolutionary stable if:

$$w > \frac{T - R}{R - P} \tag{4}$$

In such an environment any of the possible four outcomes (CC, CD, DC, and DD) occur with some probability. If the opponent using any strategy other than Pavlov and thanks to the noise beginning at any of the four mentioned situations can only lose in interactions with WSLS, then this win-stay-lose-shift strategy is evolutionary stable. Realizing that the first (defending) player uses WSLS, the attacking one chooses between two options (C or D). With the exception of two outcomes (CC and DD) when WSLS prescribes cooperation, choice other than the one made by Pavlov cannot get as large payoffs as Pavlov does. At the same time for situations of CC and DD it holds that the behavior based on WSLS strategy is the most beneficial unless (4) is false.

Bendor (1987) on the other hand analyzed effects of noise on the continuous Prisoner's Dilemma, in which you can choose the extent of cooperation instead of choosing just between two discrete options of defection and cooperation. The result was that two interacting players using TFT strategy end up with higher or at best the same variability in the level of cooperation as any pair of strategies that makes decisions not only according to the previous round as in the case of TFT, but according to the average level of cooperation from several iterations. Unlike TFT, such an averaging enables to tolerate certain amount of defections in cooperative relationship, yet it also causes slower response to eventual cooperation in defecting environment. In consequence, longer memory used during the averaging of cooperation levels enables these players to successfully spread at the presence of noise in a group that employs TFT strategy, but they must still rely on TFT players with respect to launching of cooperation in a hostile, defecting environment. The most probable final state will thus be a mixed group of actors with various lengths of memory. Those with longer memory would hinder negative effects of noise while those with shorter memory would preclude successful attacks of mean strategies (Bendor, 1987: 542). As an example of this one can think of different tolerance levels towards defection as demonstrated by foreign policies of some European states on the one hand, and that of the USA on the other.

As should be clear from what was stated above: “the precise level of forgiveness [generosity] that is optimal depends upon the environment” (Axelrod, 1990: 120). Strategies overlooking certain amount of defections in a noisy environment usually maintain cooperative character of interactions better. The question is, up to what point is forgiveness still an effective solution, and when the threat of exploitation of generosity becomes already too great? Molander (1985) tried to answer this question. He formalized noise as misimplementation of decisions and looked for such a level of generosity of tit-for-tat strategy (also GTFT) that would secure for the second, defecting player at best the same average payoff as is that of two mutually cooperating players (R). By using Markov chain computation and examining graph of quadratic function one finds out that GTFT strategy can resist the invasion if its level of generosity q is:

$$q < \min\left(\frac{\mathrm{R}-\mathrm{P}}{\mathrm{T}-\mathrm{P}}, \frac{2\mathrm{R}-\mathrm{T}-\mathrm{S}}{\mathrm{R}-\mathrm{S}}\right) \tag{5}$$

However, Molander himself noted that the extent of acceptable generosity decreases as players increase discounting of their future payoffs. And Molander in fact disregarded discounting completely by assuming the same value of present and future gains.

Pelc and Pelc (2009) used similar assumption of infinite interactions. Their article is an exception for two reasons. First of all after many years it took up again the tradition of mathematical analysis of direct reciprocity problem, but it also made use of limits instead of geometric series – a change necessitated by the absence of discount factor. Yet the article is rather disappointing with respect to innovative and interesting findings. As if the whole debate about stability was not complicated enough, they call robustness what is in fact a version of Axelrod‘s unbeatability. Strategy A is robust, according to their understanding, if for any B it holds that:

$$V(A|C) \geq V(B|C) \text{ for all } C$$

(6) or

$$V(A|C) > V(B|C) \text{ for some } C$$

While the first expression is actually Axelrod's definition of unbeatable strategy A, it is noteworthy that the second expression is de facto reformulated criteria for non-existence of unbeatable strategy B. In view of already explained Axelrod's argument about unbeatability it is no wonder then that in case of group consisting of more than two different strategies with at least two players using every one of them, then robustness becomes impossible. But the truth is that authors pay most attention to groups with only two different strategies while at the same time trying to free their analysis from the concerns of frequency of these strategies. The problem is that (6) can then be altered into the form that basically identifies robustness of rule A with the weak evolutionary stability or with the case when the other strategy is not collectively stable (disregarding of frequencies still hold true).

Added value of making the whole debate that deals with stability of strategies still more complicated is questionable. Although former concepts were conditioned by requiring specific frequencies of attacking strategies, there was a reason for doing this since not a single formulation of stability compared payoffs gained in interactions with the same rule (I mean the relationship of V(A|A) to V(B|B)). Pelc and Pelc stopped paying attention to relative numbers of players using individual strategies, but they did not compare payoffs from homogeneous pairs either. Their idea of robustness that represents the very core of their article thus raises some doubts. Nevertheless, we can still make use of their differentiation between analytical and simulation-based methods of solving the Prisoner's Dilemma (Pelc – Pelc, 2009: 775-6). I finished the review of the former, so let's take a look at the latter one, which is often employed in situations when random variables and complexity of interactions limit the power of mathematics.

2.2. Results Achieved by Multi-agent Simulations

This chapter is not the right place for giving a detailed account of multi-agent simulations of complex systems as a methodological approach in (not only) social sciences. Since the proper place for dealing with methods in this thesis is the fourth chapter, before continuing with the review and focusing on results of various models I will offer only few simple examples in order to give the reader at least some idea of what the multi-agent simulations are good for and what they can achieve.

Fine illustration of using multi-agent simulations that model micro-level interactions of individual actors in order to generate some macro-level systemic phenomena is the case from the 80s, when it was a great problem to realistically simulate the emergence of flock, movement of birds in it, and the shape and motion of flock itself. Common models trying to cope with this problem from the top-down perspective modeling the properties manifested by the system as a whole (flocks) were not satisfactory. It was only Craig Reynolds that made a breakthrough by using three simple rules of behavior of birds themselves whose interactions gradually led to the emergence of flock with unique motion and change of shape. One of the three rules regulating the movement of Reynolds' birds was actually their effort to stay within the flock (or more precisely, to stay close to other birds). This exemplifies very common relationship between agents and the system better known by the term *feedback loop.*

Another case for multi-agent simulations can be natural selection (for instance in form of proportional fitness rule) as a spreading of genes explanation based on how they increase the fitness of their possessors in competition with other individuals with other genes. Such a mechanism often leads towards change in composition of population and the new composition then reversely influences success of individual genes since it depends on what kind of opponents their possessors come across in the population. To say it in a Schumpeterian way, under certain circumstances it can thus happen that some strategies/genes will disappear precisely because of their success. They may win when playing against other strategies/genes, but lose when interacting with own copies. From a game theory point of view we can nicely see here the shift from its classical version that looks for equilibriums at the level of individual rational actors, towards evolutionary game theory that analyses development and stability of populations.

Of course many other problems are at hand, that call for application of agent-based models and related multi-agent simulations. It can be the behavior of humans for instance during the applause in the theatre, or when creating cooperating groups and social networks, or alternatively during the emergence of phenomena like segregation (Schelling, 1978). We can also successfully model development of traffic jams with help of behavior of individual agents (automobiles). Last but not least, international relations system is an example of complex system consisting of large number of independent, mutually interacting players as well. Here we can build models and run simulations of territorial growth (see the long tradition established by Bremer – Mihalka, 1977), democratic peace (Cederman, 2001), or civil wars and ethnic violence (Epstein, 2002; Bhavnani – Miodownik, 2009). Yet in the remaining part of this chapter I will be only interested in those agent-based models that deal with the emergence of cooperation in the Prisoner's Dilemma with help of direct reciprocity mechanism.

The event that set off the avalanche of models and simulations, and actually launched the research program that deals with cooperation of actors in the Prisoner's Dilemma, were the results of two computer tournaments held by Robert Axelrod. Both of them were round-robin tournaments, in which every strategy competed in binary interactions with all other rules plus with its own copy in the repeated Prisoner's Dilemma game. Players were also able to remember the whole history of their own previous interactions. Fourteen different strategies plus the rule that cooperated or defected randomly competed in the first tournament (Axelrod, 1980a). All pairs of strategies interacted exactly 200-times. Surprisingly enough, the simplest of the competing rules (TFT) proposed by Anatol Rapoport (see Rapoport – Chammah, 1965: 207) became also the winner. Fact that only the nice rules finished at the first eight places thus pushing mean strategies back on the final listing is interesting as well. Another important characteristic of successful strategies except of being nice was the ability to forgive. While for example GRIM rule doesn't forgive a single defection of the opponent and if it occurs, this ultimate retaliator defects forever, TFT on the other hand forgives just after opponent's first cooperation and immediately reciprocates.

But Axelrod (1980a) also identified three other strategies that could have won the tournament, if they had been proposed by somebody. One of them was more generous version of TFT that would retaliate only after two consecutive defections by the other player. With respect to the first tournament, interesting secondary analysis of its results offered Behr (1981). He focused upon victory defined as the number of strategies any particular player managed to beat in terms of payoffs gained in their binary interactions. In a certain way one can see here the parallel with the future relative/absolute gains debate. Axelrod looked for maximizing the sum of gains while simultaneously disregarding the opponent's fitness, Behr searched for the ability to get higher payoffs than the opponent. From the logic governing the Prisoner's Dilemma game it must then be clear that since „maximizing scores requires maximized cooperation, and achieving victories [over opponents] requires at least some willingness to defect, it seems impossible for any single decision rule to be eminently successful at both tasks“ (Behr, 1981: 299).

The second computer tournament (Axelrod, 1980b) led to a very similar outcome and this despite the fact that authors of new strategies were informed about the first tournament’s results and their analysis. 62 rules including possible winners of the previous contest as well as random strategy participated at the second tournament (actually there were 63 rules, but of them two were identical). In contrast to the previous occasion, contestants didn’t know the exact number of iterations of the Prisoner’s Dilemma but TFT strategy won again. Besides being nice and forgiving a third characteristic, namely being provocable, proved to be important as well. TFT fulfills all these requirements. It never starts defection by itself, stays always ready to reestablish cooperation, and is easily provoked to retaliate by a single defection of the opponent. In order to examine the robustness of the results, Axelrod ran six alternative tournaments with different frequencies of main types of strategies. TFT won five of them and finished second in the sixth one. Very similar results were also achieved in case of updating the strategies’ frequencies in individual games (generations) ensuing one after another according to their previous success in payoffs accumulation. TFT thus showed the effectiveness of what Trivers (1971) once called a reciprocal altruism, and this in spite of the fact that tit-for-tat has never managed to gain more than its adversary even in a single series of binary interactions (but it has never lost by more than T – S too).

Two Axelrod‘s tournaments confirmed the possibility of cooperation among egoists in the Prisoner’s Dilemma even without any enforcing authority. At the same time there remained many unsolved problems with potentially large impact upon results of future simulations (see Axelrod, 1990: 124ff, 145ff, 182-3). Axelrod’s tournaments for example ruled out the possibility of mistakes, relied on deterministic occurrence of interactions (all-play-all), and had fixed payoffs. Many of these problems were later explored by subsequent literature that carried on what Axelrod started while at the meantime also trying to follow recommendation of May (1987) to put more emphasis on non-deterministic processes. Similarly as various kinds of noise mentioned in the previous subchapter, interactions’ structure governing who actually interacts with whom can take different forms as well. It can be for instance a spatial structure, when player comes only across the neighboring actors, or it can embody various forms of network relationships of interacting players that can furthermore change during the simulations. Important position among factors influencing the results has also the pool of strategies that the model works with. More specifically, what memory do players use during the interactions; are probabilistic strategies included; or alternatively does model focus only upon few specific decision rules and their performance? This is tied to still another category of modifications that deals with a change of the basic structure of the Prisoner's Dilemma. Simple choice between cooperation and defection can be amended to include another option (e.g. exit from the game), or it can be changed from binary into continuous choice, or we can even try to amend the payoffs themselves. I would like to shift my attention now to all these factors influencing the results of simulations.

2.2.1. Mistakes in Interpretation and Implementation

The impact of noise prevailed as a key problem of models of the repeated Prisoner's Dilemma at the end of the 80s and the beginning of the 90s. Bendor, Kramer and Stout (1991) ran a similar round-robin tournament as Axelrod did before, but they formalized payoffs differently. They let players to change the level of cooperation (understood as investment in partner's prosperity) within the specified interval, but what is more important they added certain low probability of making a mistake in implementation of decisions. In accord with theoretical analysis of the impact of noise, results showed that TFT strategy fares much worse in such an environment. It was more generous strategy returning more cooperation than it received that won. Finding that „generosity works [in noisy environment] by dampening the occurrence and effects of unintended vendettas that threaten to unfold over time" (Bendor – Kramer – Stout, 1991: 706) thus generally confirmed the previous conclusions (Molander, 1985; Bendor, 1987).

With respect to conditions favoring emergence of cooperation (low noise, many iterations, favorable payoff matrix), Mueller (1987) achieved results in agreement with theoretical analysis as well. He used proportional fitness rule to change frequencies of decision rules and also many different combinations of payoff matrices, misimplementation levels, and various numbers of iterations. The model operated with two kinds of unconditional strategies (ALLC, ALLD) together with one conditionally cooperating strategy, which was examined in order to find out the optimal level of forgiveness and provocability for emergence and stabilization of cooperation. Outcomes pointed out that in a hostile environment (ALLD players) it is the unforgiving rule GRIM that can establish cooperation most easily. Yet in the further development more generous strategies can replace it because they are able to preserve cooperation, overcome the mistakes, and at the same time hinder invasion of players using mean strategies. Still, the ability to distinguish unconditionally cooperating actors increases in the importance, because even though these players promptly overcome noise, they also endanger cooperation by their own exploitability from ALLD strategies.

Repeated Prisoner's Dilemma was investigated by Nowak and Sigmund as well. Their model (1992) consisted of 100 strategies interacting with each other, capable of remembering only the opponent's very last move, and cooperating with certain probability (from 0 to 1) after each one of them. They enabled both kinds of noise, composition of the group was changed with help of proportional fitness rule, and players could count on infinitely repeated interactions (w = 1). As expected by theoretical analysis, development of collectives during simulations initially indicated success of defecting rules like ALLD. But shortly afterwards, when mean strategies were not able to get high payoffs any more because naively cooperating strategies were already eliminated, cooperation emerged thanks to TFT strategy or some other very similar one. This TFT rule that serves as a catalyst of cooperation was, however, later replaced by its more generous version (GTFT) that forgave certain amount of defections and thus prevented negative effects of noise from unrolling. Model was then extended to include strategies that during the decision making take into account also one's own last step (Nowak – Sigmund, 1993). Yet this time simulations indicated the advantages of Pavlovian strategy (WSLS) that is able to repair own mistakes but has no problem with exploiting unconditional cooperators if they are identified by noise. Although GTFT can overcome negative effects of noise, it cannot prevent neutral drift towards unconditional cooperators, which are then exploitable by mean strategies. WSLS or its modification can do that and under certain circumstances it can even resist the attack of ALLD rule that it unilaterally cooperates with every other round (Nowak – Sigmund, 1993: 58).

In the middle of the 90s Wu and Axelrod tried to sum up and compare previous results that modeled noisy environment. They wanted to determine, which of the proposed alternatives to TFT strategy is the most efficient in coping with mistakes in implementation of one's own decision. So they focused upon effects of generosity (GTFT), contrition (CTFT), and reflexivity (WSLS). Under circumstances identical with those of Axelrod's second tournament with added proportional fitness rule and different levels of noise they found out (Wu - Axelrod, 1995) that the most promising solution is contrition. In contrast to WSLS, both generosity and contrition came out as successful strategies in the environment of original 63 Axelrod's decision rules. If then one applied the mechanism of shift of strategies in the group according to achieved gains, which means gradual elimination of rules that didn't manage to effectively cope with mistakes, then CTFT surpassed even GTFT with respect to its frequency in the population. That is because GTFT offered too much of exploitable generosity in a group that included only strategies successfully overcoming mistakes in implementation. GTFT repaired own as well as opponent's mistakes, while CTFT did so only with respect to those of its own. WSLS didn't prosper in an environment with players' memory not limited only to the very last round, but this can be partly explained by the fact that the model included only mistakes in implementation and not in perception. Unlike WSLS, contrite tit-for-tat cannot repair own mistakes in interpretation of opponent's previous behavior (for analysis and simulations dealing with these two rules see also Boerlijst – Nowak – Sigmund, 1997). Thus it seems important not only what strategies interact with each other but also what kind of noise models presuppose.

2.2.2. Structure of Interactions

Structure of interaction is besides noise another important factor influencing the emergence and stability of cooperation among actors (see Cohen et al., 2001). Shortly, it determines who interacts with whom, and how often. In many situations the assumption that everybody interacts with everyone and equally often is simple untenable. Much more common is the case of stable, repeated interactions with only limited group of individuals (animals on their territory; people in their neighborhood; states on the same continent). At the same time interactions need not to be spatially defined. Many times the key is social status (students), genetic relationship (kin), or common history (Commonwealth). So far the simplest form of modeling the spatial structure of interactions in the Prisoner's Dilemma was proposed by Nowak and May (1992). Every single cell of common square lattice could use only one of two possible strategies (cooperation or defection) and this status was updated every round by adopting the strategy of the most successful of neighbors. Thus it was basically a single-round game without noise, where defection should prevail. Depending on the payoff for unilateral cooperation it was, however, possible to get different outcomes including the state of dynamic coexistence of cooperating and defecting actors. Spatial structure of interactions thus under specific circumstances enables survival of cooperation even in the environment similar to one-shot game.

Yet it was Axelrod that transformed his second tournament into toroidal space where players interacted in so called *von Neumann neighborhood* with the four nearest actors on a closed squared lattice (1990: 158-167). After every generation player adopted the most successful strategy of its neighbors, of course unless being the most successful itself. This updating of decision rules that can be also interpreted as an imitation of victorious behavior happened simultaneously for all actors. The outcome of simulation was cooperating environment, in which TFT players prospered, but the highest frequency was achieved by other, rather complicated rule that finished only in the middle of the final listing under round-robin interactions. Model similar to that of Axelrod was proposed also by Lindgren and Nordahl (1994), although they limited the memory of players to three last rounds and added the mistakes in implementation of decisions. Since they formalized strategies as a series of bits, this enabled them to include also errors during copying of neighbor's more prosperous strategy (imperfect imitation/learning). Their conclusions pointed out to very wide scope of possible outcomes depending on specific setting of parameters

Another model with mistakes of implementation and possible erroneous imitation in form of small probability to choose any available strategy instead of the more successful one was presented by Brauchli, Killingback and Doebeli (1999). Players using probabilistic decision rules with memory not longer than one round interacted in so called *Moore neighborhood* with eight nearest actors and after every generation adopted the strategy of the most prosperous neighbor. According to their findings cooperation, generosity, and reflexivity were more common and more successful in a game with spatially structured interactions than in similar models without this feature (see Nowak – Sigmund, 1992 and 1993). Thus the development of collectives and of cooperation within them is „much less chaotic in spatially structured populations" (Brauchli – Killingback – Doebeli, 1999: 412). Grim (1995) replicated the model by Nowak and Sigmund (1992) that included strategies reacting only upon opponent's last move in a noisy environment, but he added a spatial dimension to it. Similarly as Brauchli, Killingback and Doebeli he get a higher level of stable generosity than is the case in unstructured environment of round-robin interactions.

Square lattice is, however, not the only way how to model spatial structure of interactions. Works by Ilan Eshel and his colleagues are well known for using a space where players are placed at the perimeter of a circle. In one of the models (Eshel et al., 2000) they explored the possibility of cooperation in an environment with two types of players (altruists and egoists) and synchronous as well as asynchronous updating of their status by way of adopting strategies of the more prosperous neighbors. Model included accidental changes of strategy and also cases when learning neighborhood, i.e. players that are screened in order to find better strategy, differed from interaction neighborhood, i.e. players on the left and right that one interacts with. Circular arrangement of actors and their learning behavior was investigated by Hoffmann (1999) too. He used so called *finite automata* with two states (C and D) and single round memory, and formalized them into series of bits. His goal was to separate the effects of neighborhood, in which player uses its probabilistic mechanism of learning, from the one in which player interacts. Conclusion of the model claimed that under given settings the evolution of cooperation is caused more by learning neighborhood than the interacting one (Hoffmann, 1999: 66).

The last type of structure I would like to talk about and which can be at the same time better described as social rather than spatial one are so called *small-world networks* (see Watts – Strogatz, 1998) and their near akin *scale-free networks* (see Barabási – Albert, 1999). They are characterized by relatively small average distance of any two players and also greater interconnectedness of actors (*clustering*) than in case of randomly distributed networks. Round-robin tournament for example displays the lowest possible average distance between players as well as perfect interconnectedness of all actors in an environment, where everybody knows everyone, and all players interact equally often. Even though the already mentioned spatial structure of square lattice has certain local interconnectedness in case of Moore neighborhood, the average distance between players increases together with the extent of lattice. Neither of these structures corresponds very well to the reality of international relations. Currently there are for instance various groups of states whose members interact among themselves more intensely than with the rest of the world (i.e. high interconnectedness of someone's partners with each other), but none of those groups is isolated from the outside world (small average distance between any two players). Moreover, some countries interact with much higher number of different states than the others.

Structuring of interactions in a way of scale-free or small-world networks is still a new and the least explored branch of the Prisoner's Dilemma research program. Masuda and Aihara (2003) took over the approach by Nowak and May (1992) and worked only with players with no memory at all (ALLD and ALLC). Small-world network proved to be an optimal structure for spreading of cooperation in a case, when payoff matrix maximized the effect of interactions' structuring upon emergence of cooperation. Similarly beneficial impact on cooperation of actors, and even without any respect to the extent of temptation to defect, have according to recent studies also the scale-free networks that „lead to unprecedented values for the equilibrium frequencies of cooperators, such that cooperation becomes not only competitive but often the predominant trait" (Santos – Pacheco, 2005: 4; see also Santos – Pacheco, 2006). This is caused by decentralized character of these heterogeneous networks that are able to cope with the loss of some *node* without endangering the functioning of the whole network.

2.2.3. Payoffs Modification

The third but equally important factor influencing the emergence and stability of cooperation is the Prisoner's Dilemma payoff matrix itself. One of the basic alternatives how to change it is to replace simple opposition of cooperation/defection by continuous choice of investment level that gives certain benefits to interacting partner and takes certain costs from investing player. Killingback and Doebeli (2002) demonstrated the gradual increase of investments in an environment with strategies, whose current investment levels depended on payoffs in the previous round, i.e. on the level of opponent's as well as one's own investment. Ifti, Killingback and Doebeli (2004) on the other hand picked up an earlier spatial model that worked with variable levels of investment (Killingback – Doebeli – Knowlton, 1999) and examined the effects of different sizes of interaction and learning neighborhoods while using the asynchronous updating of actors. They found out that both bigger neighborhoods and also great differences in sizes of learning and interaction neighborhoods led to the lower investment levels. Their results thus corroborate „the hypothesis that clustering is the key mechanism which leads to cooperation being first established and then maintenance" (Ifti – Killingback – Doebeli , 2004: 104).

Continuous but alternating Prisoner's Dilemma, where players do not decide simultaneously but one after another (see also Nowak – Sigmund, 1994), was the point of interest for Roberts and Sherratt (1998). They introduced so called RTS strategy (*raise-the-stakes*) that increases the invested amount only in case if opponent's investment reached the same level, i.e. if the other player reciprocated. This strategy proved to be very effective at launching and spreading of cooperation in an environment with continuous payoffs. Wahl and Nowak (1999) paid attention to alternating continuous Prisoner's Dilemma too. They worked with strategies that considered only the opponent's last move, but they added the possibility of misinterpretation errors. Similarly as in the basic form of the Prisoner's Dilemma game even here (Wahl –

Nowak, 1999: 335) the path of development showed the same logic of change from mean rules towards those more cooperative ones, that are in the mean time dominated by more generous among them leading subsequently back to the possibility of successful attack of defecting rules (possible is also stable coexistence of these groups of strategies). The level of initial investment plays a significant role during the emergence of cooperation too. On the other hand, mistakes in implementation of decisions were for the continuous Prisoner's Dilemma formalized by Le and Boyd (2007), but they also achieved unstable cooperation or eventually multiple possible end-states depending on the specific setting of parameters.

The other way of modifying the payoff matrix is expanding the collection of alternative options beyond the common two (or their gradation). Robert Schuessler (1989) proposed to add the *exit option* of ending the interactions, which basically makes the game voluntary. He came up with a successful rule called CONCO that used conditional cooperation until the adversary defected for the first time, which led to the exit of CONCO player from mutual interactions. Small probability to end the interactions was added as a form of noise and there was also an imitation of successful players in a way similar to the proportional fitness rule. One of the important conclusions was that „[T]he mere ability to iterate and quit interactions may suffice to render cooperative behavior effective" (Schuessler, 1989: 747). Higher level of cooperation in the model with exit option, zero noise, round-robin interactions, and ability to remember opponent's behavior was confirmer by Batali and Kitcher (1995). Simple strategy of ending interactions after the opponent's first defection, however, becomes less effective in case of adding the *opportunity costs* into the model as did Hayashi and Yamagishi (1998). At the same time they enabled not only the exit option but also certain kind of proactive searching for a new partner.

There are of course several other possible modifications of the Prisoner's Dilemma. Frean (1994) for example changed the payoff for mutual cooperation in order to find out, which strategies are successful under various circumstances of the alternating Prisoner's Dilemma with added proportional fitness rule and certain probability that few players occasionally shift towards randomly chosen strategy. The result was a finding that with players remembering only the opponent's last move GTFT was successful if R got higher values, but with average or lower values it was ALLD strategy that prevailed. On the other hand, if the memory was extended to include also one's own previous decision, then the victory went to FBF strategy (*firm-but-fair*) that behaved like ordinary TFT rule with the only exception of being prone to cooperate after mutual defections. Still another form of changing the payoffs together with decision rules was introduced by Billard (1996), who modified the Prisoner's Dilemma matrix in such a way that its payoffs in fact represented various probabilities of getting fixed reward or penalty. Payoff for unilateral defection for instance meant guaranteed reward, while payoff for mutual cooperation offered only 75% chance of reward plus 25% chance of penalty. Probability of actor's cooperation/defection was then updated to take into account whether it was reward or penalty that had been paid out in the previous round. From the international relations point of view and with respect to modifications of payoff matrices I should finally at least briefly mention also the work by Busch and Reinhardt (1993), who examined the cooperation of players in a game with payoffs formalized according to relative/absolute gains debate and simultaneously paying attention to different values of sensitivity coefficient too. While using the strategies from Axelrod's second tournament they demonstrated the viability of cooperative behavior under various levels of relative gains sensitivity.

Modifications of payoffs as the last of the three fundamental factors influencing prospects of cooperation in the Prisoner's Dilemma game closed up the review of the most important studies that was predominantly concerned with the mechanism of direct reciprocity. Many other factors are of course able to affect the results of simulations,[4] but their applicability upon international relations is questionable. On the other hand, there still remain several models closely related to international relations that, nevertheless, do not deal with the Prisoner's Dilemma game, even though they use very similar research method of computer simulations as all of the above mentioned models. Since there already exist two comprehensive review articles (Johnson, 1999; Pepinsky, 2005) summarizing from the political science perspective the findings of these models unrelated to the Prisoner's Dilemma, I see no reason to repeat here what has been well written somewhere else.

2.3. Final Remarks

But are there any implications for the international relations themselves from the previous pages? First of all, application of the results of the Prisoner's Dilemma research program should not be limited to few catch-phrases that are usually either false,

[4] Fine example is not only the above mentioned evolutionary mechanism called proportional fitness rule, but also other factors such as learning, or imitation. They all formalize change of strategies before and during the game, and possibly even the invention of brand new behavioral rules.

or stated in a wrong context. TFT is for example not the best strategy and strict reciprocity does not always have to pay off. What is the best necessarily depends on the situation. The closer is the model to reality, the less efficient is TFT strategy for sustaining the cooperative behavior. It is replaced either by more generous, or completely different rules. As the second important fact while trying to apply findings from the Prisoner's Dilemma models upon international relations, we should think of the debate between neorealism and neoliberalism. That is because in the 80s there was an attempt to apply results of Prisoner's Dilemma simulations at the more general level to explain cooperative behavior of states as well as functioning of various international regimes (see for example the special issue of *World Politics*, 38(1) or Keohane, 1986). This attempt to reinterpret the effects of the system of states, or more precisely of the anarchical environment, however, ended up in a dead end of the relative/absolute gains debate from the late 80s and the early 90s.

The fact that we were so far unable to successfully transpose results of simulations upon the highest, systemic level of relations among sovereign states is probably the greatest drawback of the whole research program with respect to our field of study. Although more suitable expression might have been: 'a drawback of our field with respect to that particular research program'. It is because exploration of the Prisoner's Dilemma in these days goes on unhampered mainly thanks to the efforts from other fields that seem better prepared to use relevant findings and apply them in practice. System-level application of relevant findings upon international relations is not even foreseeable unless there would be a model that did not assume unrealistic interactions of everybody with everyone (or only with one's own neighbors), and unless it would also properly formalize the way how power and geography influence interactions. Fact that agent-based models of complex systems are most useful precisely for growing the systemic *macro-level* consequences out of *micro-level* processes related to individual players makes this approach even more promising as regards the study of international relations system. Attempts to apply findings of these simulations at the lower than systemic level on the other hand raise usually serious doubts.

To sum up the possibility of cooperation emergence in the Prisoner's Dilemma with help of direct reciprocity, one can identify few major factors influencing to a great extent prospects of cooperative behavior. Without trying to order these factors according to their individual importance, it is crucial to focus on the following points:

- Who interacts with whom and how often? Or in other words, what is the pattern of interactions in the population concerned?
- How stable is the nature of the game and especially the resulting gains and losses that ultimately set the fitness of interacting players?
- What strategies actors use and how they identify better alternatives, if they try to do that at all?
- And finally, to what extent are actors capable of perceiving the reality accurately and implementing their decisions properly?

One can easily find many examples how all these variables determine also functioning of the international relations and any model trying to formalize the system of states must pay close attention to them. Simply stated, it must answer some fundamental questions that our field of study asks continuously. Four issues identified above can thus be reformulated into following four questions with respect to international politics:

- Which countries/actors interact most frequently?
- What is the basic form of these interactions among states/actors?
- Is there any progress or development in international relations?
- Are states/leaders always able to properly evaluate situations they face and to achieve what they desire by choosing the right decision?

We would be able to say that the causes of war should not be seek at the systemic level (Waltz, 1959) only after adequately answering all the above mentioned questions and formalizing these answers within some model that will lead to the emergence of cooperation among players. Examined models dealing with the Prisoner’s Dilemma as well as results of related simulations I have reviewed in this chapter can help us design exactly such a model.

3. Model of International Relations

As the previous chapter suggested, there are several questions researcher must face, if (s)he intends to model the international relations system. I will try to answer these questions in this part of the thesis, in which I attempt to theoretically justify the proposed agent-based model of international relations. Agent-based models are widely used as a tool for modeling the so called *complex systems* and although few remarks were already made about these systems on preceding pages, I will explore them deeper here. Then I will briefly look at the possibility to reconcile, or maybe rather to find a common ground between, rationalistic and constructivist theories. Since many agent-based models including this one are based on game theory, which is undoubtedly a rationalist approach par excellence, my attention will be more focused upon constructivism and what it shares with complex systems. After clarifying the issue of complex systems and how constructivism relates to that and to rationalist theories, I'll proceed to agent-based modeling as the best way of both analyzing the complex systems, and unifying the insights from rationalist and constructivist theories.

Design of the proposed game theoretic model of the international relations system is described in three core sections of the present chapter. They are dedicated to agents, environment, and rules. It can be seen from the preceding chapter that many important features of the international relations system have been already formalized in one way or another. Unfortunately, they were not designed with the system of states in mind. For example, there are many different ways of modeling spatial nature of interactions. Various ways of changing the payoff matrix during the simulation exist as well, and two effects of noisy environment represent no breakthrough for experienced agent-based modeler either. However, very few models (if any) put these features together and formalized them in such a specific way as to resemble the system of international relations. My intention is to do precisely that.

In my model, actors with various strategies represent states and they interact in the dyadic, repeated, and simultaneous Prisoner's Dilemma game receiving symmetric payoffs and thereby increasing their capability levels. Occurrence of interactions is determined by agents' power and spatial position so that the most powerful states closest to each other interact most often. Some added probability of misperception as well as own misconduct makes model more dynamic and simultaneously more realistic. The same holds also for shifts of payoff matrix according to the previous history of interactions, when mutually cooperative behavior pushes matrix more closely towards Assurance game, while defection shifts it towards another limit of Deadlock.

To use Wendt's ontological classification of international relations' theories (1999: 29) according to effects that structure and ideas are supposed to have, proposed model will try to stay at the border of both materialist/idealist, and holist/individualist division. Although the model rests upon bottom-up individualism of interacting agents with their success understood in a materialist way as a power manifested through the level of accumulated gains, the model at the same time tries to formalize cultural relations of friendship and enmity as a structural variable influencing, and resulting from, the players' interactions. As regards possible third ontological choice between stability on the one hand and dynamic processes on the other, I clearly opt for the latter. Finally, my agent-based model of the international relations system is based on game theory, but its character as an example of formal theory would become apparent only in the third, methodological chapter, where all variables presented here are translated into the language of mathematical formulas. In this chapter I try to focus merely upon written description and justification of various features of the model.

3.1. Dealing with Complexity

I already wrote in the previous chapter that the international relations system is an example of a complex system. But what exactly does it mean for a system to be *complex*? Several authors from international relations dealt with this problem in one way or the other (Jervis, 1997; Kavalski, 2007), yet it is still the Herbert Simon's definition that makes the point most clearly:

> [B]y a complex system I mean one made up of a large number of parts that have many interactions. … [I]n such a systems the whole is more than the sum of the parts in the weak but important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer properties of the whole. (Simon, 1996: 183-4)

In this definition we can find almost all the characteristics ascribed to complex systems also by other authors. For example Forrest identified three features of complex systems to what Gilbert added another property of *emergence*. Those three features are:

1. The system consists of a large number of interacting agents operating within an environment. Agents act on and are influenced by their local environment.
2. There is no global control over the system. All agents are only able to influence other agents locally.

3. Each agent is driven by simple mechanisms, typically condition-action rules, where the conditions are sensitive to the local environment.

(cited in Gilbert, 1995: 124-5)

It is, however, emergence that is one of the key concepts when dealing with complexity and it is basically this that Simon had in mind, when he spoke about the whole being ‘more than the sum of the parts’ (see also Jervis, 1997: 12-15; Hamman, 1998: 179-181). In other words, when agents in a complex system interact at the micro (individual) level, their interactions may lead to unintended phenomena at the macro (systemic) level that cannot be analyzed or grasped by the same tools as used at the lower level of individual interactions (see also Axelrod, 2003). Fine example of this macro-structures emerging out of micro-behaviors is in the previous chapter mentioned segregation as modeled by Schelling (1978) or for example traffic jam brought about by interactions of individual cars. According to Gilbert and Troitzsch then:

> Emergence occurs when interactions among objects at one level give rise to different types of objects at another level. More precisely, a phenomenon is emergent if it requires new categories to describe it which are not required to describe the behaviour of the underlying components. For example, temperature is an emergent property of the motion of atoms. An individual atom has no temperature, but a collection of them does. (2005: 11)

Multiple agents and emergence are the most commonly mentioned characteristics of complex system, but there are few others, similarly important ones. Crucial role of interactions was mentioned by Axelrod (1997) and Simon’s concept of complexity as hierarchy was based on a very similar idea. He defined hierarchy not in sense of domination-submission relationship, but as a pattern of interactions and their intensity (Simon, 1996: 184-7). It was, however, Robert Jervis (1997: 17-19) who put interconnectedness besides emergence as the second defining feature of complex systems. This interconnectedness is again a kind of interactions’ occurrence pattern that causes agents and their local environment to be influenced and shaped by interactions of other players, at other places, and/or at other times, which renders isolation of any particular part of the system virtually impossible.

Another peculiarity of complex systems are feedback loops (Kavalski, 2007: 438). If interactions of units on the one hand lead to emergent phenomena at the systemic level, feedback loops on the other hand mean that changes at the systemic level in return influence behavior of units. Very nice example is overall balance between various predators and their preys in nature. For instance if the population of deer increases because of abundance of resources, the same will happen also to wolfs with some delay since deer are in the prey-predator relationship with wolfs. However, as the population of wolfs grows in numbers, their prey becomes scarce and its pool depleted because of the higher pressure from predators. Feedback loop of scarce prey then causes decrease in population of wolfs, which in return after some time again enables higher reproduction rates of deer. Similar feedback mechanisms exist in most of the complex systems. Last but not least, nonlinear and highly interwoven relationships are together with bounded rationality in case of human interactions associated with complex systems too (see Kavalski, 2007; but also Jervis, 1997). That all must be blamed for rather poor results of traditional modeling approaches and for deficiency of suitable mathematical tools applicable upon complex system.

In sum it is the emergent phenomena, multiple independent agents interacting in complicated patterns, feedback loops, nonlinearity, and probabilistic events that together form systems that can be called complex. But how does international relations system fit into this? First of all, there is undoubtedly large number of states in the system even though it was not always as large as it is now. Interactions of states are hugely complicated as well and are influenced by historical ties, great powers' interests, border disputes, economic issues and many others. Interconnectedness can be exemplified by 9/11 that brought US and other NATO member states' troops into mountainous, underdeveloped, and distant Afghanistan. You can hardly think of better illustration of feedback loop mechanism than is the one present in a security dilemma or in any arms race, when presence of arms in hands of enemy leads state to strive for security by acquiring the very same weapons, which in return further heighten insecurity in the system. There is similarly no sure thing principle, no full rationality, no perfect knowledge of the environment, no predictable way from intentions to outcomes either. Certainly not after superpowers losing wars in Vietnam and Afghanistan, Japanese attack on Pearl Harbor, sinking of Kursk nuclear submarine, or the first battle of the Marne. It is in fact the life-long work done by Robert Jervis that shows the complex character of international relations system most clearly (see particularly Jervis, 1997; but also Jervis, 1976). Yet the hardest case for applying complexity metaphor upon international relations is emergence. Jervis actually passed the buck to others by merely focusing upon interconnectedness. But we can still find possible examples of emergent properties when dealing with states and their interactions. The first and potentially the most promising illustration might be emergent hierarchy (as Simon understood it) of great and lesser powers that unfolds throughout the history. Usual peace among nations disrupted only by occasional hegemonic wars might be another example, and some would certainly assert that the same holds also for balance of power as a consistent tendency of the system towards multiple centers of power and away from hegemony. Thus we have due reasons to perceive the system of states as a complex system.

After making clear what I mean by complex systems and why the international relations system can be viewed as an example of that, I can now proceed and take a short look at the uneasy relationship of rationalism and constructivism in the international relations theory and how it can be improved by the agent-based modeling. Best way how to do this is to follow the lead of Fearon and Wendt (2002). Rationalism is (in social sciences) naturally associated with *individualist* game theory, but with respect to international relations theories it is actually (neo)realism and its counterpart neoliberalism that comes to our mind first. Great share of responsibility for that goes to usually unnoticed difference between instrumental rationalism of game theory, and its substantive version in neorealism (see Keohane, 1988: 381). Paradoxically, Waltz's effort (1979) to put his *structural* realism on rigorous scientific foundations required by Karl Popper with respect to natural sciences, and also the late 80s and early 90s debate about relative and absolute gains that included some technical formalization and game theoretic reasoning, only contributed to this identification of rationalism with neorealist theory (for alternative interpretation see Albert – Cederman, 2010). In spite of Waltz's obvious structuralism, his theory is for some still compatible with individualism (Wendt, 1999: 31; see also 1987) and thus Wendt locates the debate between neorealist and neoliberal views into individualist quadrants of his table classifying different theories of states' relations (1999: 32). At the end, even for those that identified rationalism with what Wæver called the neo-neo synthesis (1997: 163), individualism became the cornerstone of the former (Wendt, 1999: 27). Fearon and Wendt later highlighted the same when they stated that:

> a more plausible candidate for a constitutive feature of rationalism is a commitment to explaining macro-social phenomena in terms of more micro-level phenomena (Fearon – Wendt, 2002: 56; see also page 53)

In fact, individualism, occasionally accompanied by self-interested utility maximization assumption, pays key role in basically all current attempts to define rationalism (e.g. Jupille – Caporaso – Checkel, 2003: 12; Abell, 1992: 189; Albert – Cederman, 2010: 6).

Individualism is also the reason why game theory as a rationalist approach was so successful as a tool for understanding and modeling the complex systems, because these systems are similarly as game theory based upon micro-level interactions that only subsequently lead to macro-level outcomes. Bottom-up rationalist approaches focus upon causes of behavior rather than causes of preferences since “[M]ost individualists treat identities and interests as exogenously given” (Wendt, 1999: 27; see also Ruggie, 1993: 140) and thus leave this problem of how preferences are shaped to constructivists.

> [T]he rationalist strategy is usually to build in or presuppose some social structures and the identities they constitute, and then to explain from the ‘bottom-up’ a pattern of choices and the structures they imply. Constructivists have objected to this building in of structurally constituted identities, since they are interested in how these are constituted in the first place. (Fearon – Wendt, 2002: 66)

But contrast between individualism and holism (or rather structurationism) is not the only difference of rationalism and constructivism. While the former is concerned first and foremost with causal relations, the latter pays much more attention to constitutive mechanisms of how agents and structures mutually shape and reproduce themselves. Rather than examining stable end-states and how actors got there, constructivists and their ‘theories of action’ analyze processes of how interests and identities change (Jupille – Caporaso – Checkel, 2003: 14; Wendt, 1999: 36; Hopf, 1998: 181 & 196). In their understanding neither interactions of agents can be wholly determined by structural constrains, nor structure is fully reducible to interactions of individual actors. They are both in a mutually constitutive relationship. The role of bridge between agents and structure is served by rules (either constitutive or regulative) and related practices:

> Constructivism holds that people make society, and society makes people. This is a continuous, two-way process. … To make a virtue of necessity, we will start in the middle, between people and society, by introducing a third element, *rules,* that always links the other two elements together. Social rules … make the process by which people [agents] and society [environment] constitute each other continuous and reciprocal. (Onuf, 1998: 59).

Finally, if these rules and practices that govern and represent behavior of actors are stable enough they turn into institutions that “make people into agents *and* constitute an environment within which agents conduct themselves rationally” (Onuf, 1998: 61 emphasis in original). Constructivism can thus be characterized as focusing upon process of reproduction and change of identities and interests via rules and practices that mediate mutually constitutive relationship between agents and the environment (notice that neorealists see only agents and structure, not rules; Waltz, 1979: 79). Yet it still has to be explained how all this relates to complex systems and agent-based modeling itself.

In order to take a grasp of complicated things we usually design their models. According to King, Keohane and Verba "[a] model is a simplification of, and approximation to, some aspect of the world" (1994: 46), which in this case are relations of states to each other. Agent-based models (see Tesfatsion – Judd, 2006 eds.; Axelrod, 2003; Epstein, 1999; Cederman, 2005) are simplified versions of complex systems and similarly as in the case of constructivism they are defined by agents, environment, and rules (Epstein – Axtell, 1996: 4; see also Gilbert – Terna, 2000: 67-69) that govern agents' behavior and regulate functioning of the environment. In any model scholars usually formalize only the most fundamental properties of complex systems so that final design meets the KISS maxim of *keeping it simple and stupid* (Axelrod, 1997: 4-5). Agent-based models also start with the bottom-up principle, which makes possible both the method of multi-agent simulations as a data gathering tool, and the application of insights from game theory with which it shares the position of methodological individualism to some extent.

> However, we part company with certain members of the individualist camp insofar as we believe that the collective structures, or "institutions," that emerge can have feedback effects in the agent population, altering the behavior of individuals. Agent-based modeling allows us to study the interactions between individuals and institutions. (Epstein – Axtell, 1996: 16-17)

Feedback loops as present in most of the complex systems and therefore formalized in agent-based models as well highlight the mutual shaping of agents and structure, and represent yet another similarity between constructivism and agent-based models of complex systems besides that of virtually identical crucial components – agents, environment, and rules. In words of Macy and Willer: "ABMs defy classification as either micro or macro but instead provide a theoretical bridge between levels" (2002: 148). The truth is that compatibility of constructivism with modeling of complex systems had been pointed out from both sides. On the one hand, Hamman stressed the usefulness of complexity as an inspiration for constructivists and he believed in "a possible isomorphism between constructivism and emergent science's elaboration of complex dynamic systems." (Hamman, 1998: 190) On the other hand Gilbert (1995) showed that structuration theory of Giddens, which profoundly influenced Wendt and other constructivists, could serve as an inspiration during the designing of models of human complex systems. These are the reasons why I regard agent-based modeling of complex systems as not only compatible with constructivism, but also as a promising way of reconciling rationalist and constructivist theories.

Proposed agent-based model of the complex international relations system strives to accomplish exactly that. To use the words of James Morrow, in the following model I try to “capture the essence of a social situation” (1994: 7), in which actors are sovereign states. Model rests on game theoretic foundations and thus carries on the tradition started by two Prisoner’s Dilemma tournaments of Robert Axelrod that showed the possibility of cooperation among egoists. But as Duncan Snidal rightly warned:

> Applying game theory to a substantive body of knowledge such as international relations raises a host of difficult empirical questions. For example: Who are the relevant actors? What are the rules of the game? What are the choices available to each actor? What are the payoffs in the game? Is the issue best characterized as single-play or repeated play? (Snidal, 1985: 26)

As he later emphasized, any model of international politics based on game theory must pay close attention to how structure on the systemic level relates to voluntaristic decisions at the unit level (Snidal, 1985: 40). Similarly, Robert Hoffmann (2000) identified key factors that determine outcomes of agent-based models and whose modifications distinguish various models from each other. These factors encompass agents representation including their strategies, composition of the initial population of actors, structure of their interactions, the way how their rules of behavior change, payoff matrix, iterations, and noise (see also Axelrod – Dion, 1988). Finally, Rasmussen as well identified three minimum requirements for describing any game to be a definition of players (agents), available actions and information determining the payoffs (environment), and strategies (rules) (1989: 22). In next three subchapters I design all these factors with a specific idea of international relations system in mind. Resulting model is at the same time an attempt at what Jupille, Caporaso, and Checkel (2003) called a theoretical conversation between rationalism and constructivism. More precisely, out of the four modes of conversation my model is an attempt at a sequential approach that tries “to build a more comprehensive composite … all the while preserving the integrity of the contributions of the parts“ (2003: 19) and simultaneously suggesting “that variables from both approaches [rationalism and constructivism] work together over time to fully explain a given domain” (2003: 22).

3.2. Agents

My model is agent-based so there must be some agents that interact with each other and have specific qualities particular only to them (see four basic assumptions of ABMs according to Macy – Willer, 2002: 146). Epstein and Axtell (1996: 4) defined agents as the units of artificial societies that possess certain (possibly alterable) internal states and specific behavioral rules while according to Wooldridge and Jennings actors in agent-based models are generally characterized by the following four properties:

> - *autonomy*: agents operate without other players having direct control over their actions and internal state;
> - *social ability*: agents interact with other agents through some kind of formalized processes or 'language';
> - *reactivity*: agents are able to perceive their environment (which may be the physical or a simulated world) and respond to it;
> - *proactivity*: as well as reacting to their environment, agents are also able to take the initiative, engaging in goal-directed behavior.
>
> (cited in Gilbert – Troitzsch, 2005: 173)

Onuf as a constructivist for example understood agency as a social condition of capability and willingness to "act on behalf of other people" (1998: 60), but at the same time agents in his view do not necessarily have to be individual human being. Since I model international relations system, the agents in my model are states and they act on behalf of their population. Both rationalist and constructivist theories agree that states are maybe not the only one but certainly the most important units in international relations. In words of Alexander Wendt "it makes no more sense to criticize a theory of international politics as 'state-centric' than it does to criticize a theory of forests for being 'tree-centric'" (Wendt, 1999: 9; see also Waltz, 1979: 93-95; Keohane, 1984: 25). And although the truth is that "rules tell us who the active participants in a society are" (Onuf, 1998: 59), I don't want to get involved into the debate about what are the necessary and sufficient conditions for entity to be regarded as a sovereign state, or the one about the very meaning of sovereignty itself. There are certainly many ambiguous cases but I could hardly settle the dispute here in what extent is Kosovo a sovereign country in contrast to let's say South Ossetia. Moreover, I don't even see the reason to do that unless I try to model particular states, which I won't. Basically I agree with Waltz on what he said about sovereignty:

> To say that a state is sovereign means that it decides for itself how it will cope with its internal and external problems … States develop their own

> strategies, chart their own courses, make their own decisions about how to meet whatever needs they experience and whatever desires they develop. (Waltz, 1979: 96)

Trying to find a better illustration of correspondence between assumed autonomy of actors in agent-based models and the system of states seems futile. What is also important is that similarly as in reality the model will include multiple agents (see the first defining feature of agent-based models as listed by Gilbert, 1995: 124-5) so that their interactions would be both numerous and heterogeneous enough.

Few lines have to be reserved for the properties of actors as well. Except for four above mentioned attributes of agents I also pay attention to players' goals, rational conduct, power capabilities, and spatial character. First of all, Waltz call states 'like units' because they are all autonomous political units with an attribute of sovereignty. Although they differ in size, wealth, power, and form, they "are alike in the tasks that they face, though not in their abilities to perform them. The differences are of capability, not of function." (Waltz, 1979: 96) The problems begin with specifying the function or goal of the states. For Waltz it is survival/security (1979: 91 & 126) and he derived this rather self-evident *ultimate goal* from how the structure of international politics works. Even though Fearon rightly pointed out that despite being a reasonable assumption this ultimate goal of states is in fact "not a consequence of anarchy or international structure" (1998: 294), I see no trouble in accepting it. Yet how states achieve this ultimate goal? It is here that the issue of *proximate goals* comes forth.

Waltz contends that it is by maintaining one's own position in the system and not by maximizing power (1979: 127) that states earn security. In contrast, Mearsheimer as an offensive realist argues that out of his five fundamental assumptions, that include already mentioned ultimate goal of states, one can infer the proximate goal of power maximizations as the most promising behavior of countries trying to achieve security (Mearsheimer, 2003: 33-36). I don't agree with either interpretation of proximate goals. The best way how to gain security depends upon whom the agents interact with. You won't make many friends, if you always try to outcompete them, and you won't be able to keep them, if you mind that they are successful. And that there are friends similarly as foes in the international politics is equally self-evident as the ultimate goal of security. Achieving security requires cooperation when dealing with friends and the opposite when dealing with foes. Security can only be the result of appropriate behavioral rules. Neither balancing nor bandwagoning are natural outcomes of the structure of international relations system. They are individual strategies of state's behavior. I will deal with strategies and enemy/friend opposition in the subchapter dedicated to rules that connect agents with their environment. With respect to properties of agents it is only important to note that their social ability, reactivity, and proactivity is in my model reflected in the fact that each state has some strategy or rule of behavior and that agents have also sufficient memory to remember all of their previous interactions. As regards power maximization, I paradoxically agree with Waltz when he said that "[I]ncreased power *may or may not* serve" the ultimate goal of security (1979: 126 emphasis added), but at the same time I still believe that it is a useful way of classifying states. Model will make use of it by sorting out the agents according to the level of capabilities (game payoffs) they reach in the simulations.

To get back to properties of states, let's focus upon instrumental rationality first. For actor to be considered rational, (s)he must order her/his preferences over outcomes of all available choices in a transitive manner and decide, which action to choose so that her/his utility would be maximized. Assumption of actors behaving like perfect utility maximizers represents maybe the most often criticized part of models based upon rational choice theory (see for example Varoufakis – Hargreaves Heap, 2004: 15ff). Concepts like trembling hand, bounded rationality, and prospect theory sought either to pinpoint false postulates of instrumental rationality or to bring it closer to reality. Nevertheless, it was no one other than Robert Axelrod (1990: 17-18), who stated that rationality is in no way required in his model. The same remains true also in the present case. In agent-based models generally and in my model in particular, agents don't know in advance with whom, how often, and under what conditions they will interact with. Thus they cannot purposefully maximize their utilities because they don't have necessary information for doing that and not even the using of probabilities can help them solve this problem. The simpler and fewer assumptions model has, the better it usually is. Lack of instrumental rationality certainly won't impair the realistic nature of the model presented. Quite the contrary!

The last remaining attribute of players in my model that reflects states in the real world is their spatial character. Territory symbolizes one of the crucial qualities of statehood. Contrary to models of Bremer and Mihalka (1977) or Cusack and Stoll (1990), states in my model do not expand their territory or split apart as a consequence of war. My intention is not to model war or crisis escalation so I designed actors to be similar with respect to territorial extent as well as number of neighbors, and assumed that they would remain so. Hence I follow the lead of Waltz (1979: 99) and "abstract from every attribute of states [that enables their distinguishing] except their capabilities." Since I already dealt with the capability levels of states, all other properties of states are either disregarded or assumed to be similar for everyone. In case of spatial character of states I focus on relative position with respect to other agents rather than on the extent of territory. But position vis-à-vis other agents (states) is similarly like distribution of power not a unit-level variable and thus it will be analyzed elsewhere. Furthermore, I see no reason why to regard extent of territory as one of the most important factors in the system of international relations. True:

> [p]rior to the modern age, and particularly prior to the Industrial Revolution, conquest of territory was the primary means by which a group or state could increase its security or wealth. … In fact, until the technological revolution of the late eighteenth century, the international distribution of territory and the distribution of power and wealth were largely synonymous. (Gilpin, 2002: 23)

But this is not the case any more. Germany has basically the same area as Vietnam (they are alike even in size of populations), and still their impact upon international politics is incomparable. Shifts in capability levels can be, moreover, easily understood as incorporating also the possibility of territorial change, even if this is increasingly rare today. Similarly, when speaking about importance of geography, most scholars have in their minds the ability of particular geographical features (oceans, mountains etc.) to separate states and hinder or facilitate their cross-border interactions. I don't want to mingle with the critical geopolitics and its interpretation of spatializing practices of classical political geographers from Mahan and Ratzel to Mackinder, Spykman and beyond (Ó Tuathail, 1996), even though I consider critical geopolitics enormously insightful with respect to unveiling the (in)stability of what particular geographical features represent. I simply regard geographical particularities of individual states as not important enough to be included in the model. Their meaning and significance is anything but fixed. It shifts in time and context, and is usually only a result of other, more important traits present in the international relations system of states.

How borders are drawn is for instance often a matter of chance, prevailing power interests, and/or simple disregard of conditions *in loco*. You don't even have to look for examples to Africa and its colonial era borders drawn on a principle 'first come, first served'. Central Europe is immensely inspiring as well. Of course, you have the city of Berlin divided for almost thirty years by wall, but what is that compared to pushing the whole Poland hundreds of kilometers westwards after the WWII or demarcating boundary between Czechoslovakia and the Soviet Union in 1946 right through the 700 years old village of Slemence that for next sixty years lacked even a simple pedestrian border crossing. Arc of the Carpathian Mountains looks like a perfect natural boundary and actually for centuries it represented the border of the Kingdom of Hungary. Although Russian army managed to cross the mountains in the early 1915 and captured few cities in what is now eastern Slovakia, the same feat was enormously hard to accomplish for Red army in the WWII as exemplified by the battle of Dukla pass. Yet after the first partition of Poland the Habsburg Monarchy acquired Galicia just north of the present day Slovakia and hence for many years abolished the role of northern Carpathians as a bordering region. Treaty of Trianon did the same with respect to southern Carpathians by redrawing the border between Hungary and Romania.

I intentionally restricted myself to fewest possible assumptions about agents. As obvious from what has been written above, trying to model geographical particularities of individual actors, which seem more to reflect the influence of other variables than being a defining feature of international relations on its own, invokes a strong feeling of pointless enterprise. Therefore, states in my model have spatial character that enables formalizing their position, but they are alike with respect to all other geographical characteristics like number of neighbors or extent of land area. Agents also demonstrate certain level of capabilities, which renders their classification possible. And finally, they can use their memory as well as some rule of behavior in interactions with other players. Rationality is in no way a necessary condition.

3.3. Environment

Image gets a bit more complicated when we start inquiring into the system. In this subchapter I sketch the way how to analyze environment of states. I say environment because I do not consider word *structure* to be an adequate description of what must be taken into account when dealing with systemic level of international relations. In this thesis, but also in other agent-based models generally, the environment:

> "could be landscape, for example, a topography of renewable resource … However, the environment, the medium over which agents interact, can be a more abstract structure, such as a communication network whose very connection geometry may change over time. The point is that the "environment" is a medium separate from the agents, on which the agents operate and with which they interact." (Epstein – Axtell, 1996: 5)

Again, this definition nicely demonstrates the common ground between agent-based modeling and constructivism in that agents interact not only with themselves but also with the environment, and that the character of the environment can change over time thanks to those very same interactions. I understand this medium as containing both structural and non-structural elements, even if both exist on the systemic level. An example of the first is payoff matrix, an example of the second is noise. I deal with them in the same order, but first I need to explain what I mean by the structure itself.

As already pointed out, Waltz recognized only units at the micro-level and structure at the macro-level as two constitutive parts of the system. While focusing on the structure in order to offer analytically better concept replacing allegedly vague ideas like that of environment, or milieu, he identified three variables capable of bringing about change of the system (his theory completely disregarded particularities of agents). These are *ordering principle*, which in case of international relations is anarchy, *functional specification*, which is nonexistent among states, and finally *distribution of capabilities*, which corresponds to preeminent position of great powers (Waltz, 1979: 100-101). Such a definition of structure is, however, more harmful than helpful and Wendt rightfully criticized Waltz for delimiting reductionist theories as those concerned with properties of agents *and/or* their interactions (Wendt, 1999: 145; see also Waltz, 1979: 18). In trying to make a clear distinction between levels of analysis Waltz destroyed all the bridges usually represented by interactions, rules, and practices that connect units with structure. He thus rendered his theory extremely static both with respect to change in distribution of capabilities as well as with respect to mutual constitution of agents and structure (see Ruggie, 1983; Gilpin, 2002).

> One problem with Waltz's formulation of the unit-level / structural distinction, therefore is that it 'reifies' structure in the sense of separating it from the agents and practices by which it is produced and reproduced. … The other problem is that by assigning the study of interaction to the unit-level, a topic that has an inherently outside-in [emergent] aspect is removed from the definition of the systemic project. (Wendt, 1999: 146)

Waltz merely described how the international relations system looks like, but not how it evolves in time. Though, Wendt's reformulation of argument that concerns structure didn't help either. He tried to reconcile individualist and holist views with help of Giddens and his structuration theory. According to Wendt, structure should be analyzed by means of two levels (micro and macro), two effects (causal and constitutive), and two things (behavior and properties). This division gives us two 2x2 matrices. One for macro structure of multiple realizable outcomes and the other for micro structure of agents' interactions. Rational choice theories are situated in the latter's upper-left corner that is concerned with causal effects of interactions' structure upon states' behavior, while constructivism is placed in the former in its lower-right corner focused upon constitutive effects of macro structures on properties of actors. Such reconceptualization of structure is maybe better or more justified view of the systemic level of international relations than that of Waltz, but certainly not more comprehensible or definitive.

I have no problem realizing the importance of interactions for any model of international relations and I perfectly understand that these interactions can have structure on their own. But the label 'structure of interactions' used by Wendt is not the best name for what he had in mind, since *structure of interactions* in agent-based modeling commonly denotes stable pattern of interactions occurrence (who interacts with whom and how often) rather than the way how gains and losses of individual players are strategically interdependent (as for example in the Prisoner's Dilemma). Unfortunately, Wendt used the term 'structure of interactions' in the latter, not in the former context. At the same time I consider Waltz's characterization of structure of international relations system to be more useful for further development than that by Wendt. Even though it is not as all-embracing as the latter one, it is nevertheless more intelligible and much easier to modify into the form, in which it will become highly plausible. Moreover, what Wendt meant by micro level of interactions is the very same thing I want to add to Waltz's three definitional features in his portrayal of the international relations structure. Such a modification will overcome the precarious neorealist subsumption of interactions under unit-level of analysis, while trying to keep as much as possible from Wendt. The following matrix represents four main structural characteristics that I would use when dealing with international relations. And although

		Recognition	
		Static	*Dynamic*
Level of Change	*Structure*	Distribution of resources	Interaction Space
	System	Ordering principle	Functional differentiation

Figure 2: Analyzing Structural Characteristics

I'm primarily concerned with international politics, I believe the modified version of Waltz's ideas can also put some light on structures in general.

As apparent from Figure 2, we must approach system's structure of the model proposed in this thesis from two different vantage points simultaneously. We need to distinguish structural characteristics both from point of how we can recognize these features themselves, and also from a point of possible impact that changes in these characteristics can have on the system. Hence we get four structural factors: interactions space, distribution of capabilities, functional differentiation, and ordering principle, of which the last three correspond to what has Waltz written about structure of politics (see chapter 5 in Waltz, 1979). Necessarily, such a fourfold conceptualization of structure is first and foremost an analytical convenience. No strict separation exists between individual features. Functional differentiation of agents is usually related to ordering of the structure, yet these two characteristics can be, nevertheless, better analyzed separately since they focus on different aspects of structure. The same holds also for possible relationships between distribution of resources and ordering principle, or between the latter and interaction space. After all, even if formalizing mutual interdependence of these four features can further enlarge the scope of the model to include periods when system was not dominated by sovereign states, this is not a goal of my thesis that pays attention to the system of territorial states.

Let me explain four above mentioned defining characteristics of structure more thoroughly. Since I believe in their applicability upon structures generally, I will also use several examples of other systems (besides that of international relations), whose structures can be analyzed in the same manner. First, I distinguish structural characteristics by the way how they can be recognized. Both, distribution of resources as well as ordering principle, are static variables recognizable by observing the status quo in the system. Conversely, interaction space and functional differentiation are dynamic features that can be identified and described only by observing how agents interact in practice. Second, I make a difference between ordering principle and functional differentiation on the one hand, and distribution of resources and interaction space on the other. This difference is based on the impact that possible changes in these characteristics can have. In other words, it concurs with distinction between what Waltz called systems change and change (of structure) within the system (1979: 100-101). Any modification of ordering principle or functional differentiation leads towards systems change. Variations in distribution of resources and/or interaction space bring about only changes of structure, not of the whole system (see also Gilpin, 2002: 39-40).

For better understanding of what I mean by four structural characteristics that results from two distinguishing categorizations we need to look at the international relations system and maybe some other examples as well. Starting from functional differentiation of its agents, Waltz rightly claimed that states in the international relations system are like units with respect to what they strive for - security. The same holds also for firms trying to increase their profitability on the market, but transport routes (viewed here as agents of traffic infrastructure) in form of railways, highways, air corridors, or pipelines, all serve to transport different cargo in a different way and are thus functionally different too. Dynamic nature of functional differentiation is apparent only after actually seeing states (agents) performing their choices of action. Only then you can realize that they are like units. Now imagine that there are states in the system that don't care about security (being a friend of somebody and therefore seeing its security as interconnected with one's own is not the same thing). If in such an environment these actors survive and are not eliminated, then this represents an enormous change of the system (probably towards a hierarchic one), because under present conditions any such a state is infinitely exploitable. As Waltz put it:

> Hierarchic systems change if functions are differently defined and allotted. For anarchic systems change derived from the second [functional] part of the definition [of structures] drops out since the system is composed of like units. (1979: 101; see also 104)

Of course in reality there are different degrees and examples of striving for security. Great Britain provided security for its colony of India until it became independent unit of the system. In reverse, Czechoslovakia was an independent state but it failed to fight for its security both in September 1938, and March 1939 with outcome of losing its own sovereignty. The same happened to the same state also in August 1968 even if its lacking independence in foreign policy was already obvious for long. The question here is not whether the result would have been different, if Czechoslovakia fought for its freedom. The issue is much more how possibly could have Czechoslovakia *survived* without interest in its own security unless in a completely different system.

With respect to ordering principle, anarchy as a metaphor for international relations system is universally accepted. Effects of anarchy, on the other hand, are undisputedly less settled. For Waltz the anarchy is a self-help system where "[T]he international imperative is 'take care of yourself'" (1979: 107), which results in balancing behavior. Wendt, however, argues that neither self-help nor balancing follows logically from anarchic structure of international politics, and that they are merely results of states' repeated interactions (1992: 394-5). Although I agree with Wendt in general, I don't need to solve this problem here in any detail. The issue of what anarchy leads to is related to interactions, behavioral strategies, and other rules governing the system, which will be dealt with in the next subchapter. For now it suffices to say that there is no supreme authority above sovereign states as independent agents in the system. What has already been said is that change in ordering principle represents systems change, such as from anarchy to hierarchy, and is often connected with functional differentiation. What has not been said is that to recognize anarchy among states we just need to look at the status quo in the system and see that there is no policing corps that enforces universally applicable rule of law and no courts to authoritatively settle disputes among nations. Although Allies of the WWI, International Court of Justice, and resolution by arbitration influenced the border dispute between Czechoslovakia and Poland in the 1920s in regions of Cieszyn Silesia, Orava, and Spis at least as greatly as outcome of the Seven-day war, none of that prevented Poland from taking its part of Czech cake during the Munich crisis in autumn 1938. In a similar manner Slovakia eagerly assisted Nazi Germany in its attack on Poland in September 1939 and annexed parts of Polish territory adjacent to regions of Orava and Spis. In 1945 the Czechoslovak-Polish border returned to pre-1938 status but it was only the *bilateral* agreement between them that definitively ended the dispute in 1958.

Nonetheless, there are still great powers with huge impact all around the world. Together with less powerful states that hardly interact with their own neighbors they give birth to what is called distribution of resources. Waltz called it distribution of capabilities (1979: 97ff), but unless we want to apply it only upon the system of international relations, the term *resources* is more appropriate than *capabilities*. Resources is a more general term that can include states' power, market share of a company, or various forms of capital (Bourdieu, 1999) in human societies. All of them are structural, or more precisely relational, phenomena (for relational character of power see Gilpin, 2002: 158). In case of international relations, level of capabilities (payoffs gained) is a way of classifying states as agents in my model. And this level of capabilities is justly seen as a property of agents. Yet power is a structural variable par excellence and it is defined by the *distribution* of capabilities in the system (Waltz, 1979: 192 and also 98). This distribution can be similarly as ordering principle recognized usually by a simple observation of status quo and some even attempted to quantify it (Singer, 1987). One didn't need to wait until September 1, 1939 to know that if Nazi Germany decided to attack its eastern neighbor, Polish cavalry would not be able to stop German Wehrmacht. Distribution of resources nevertheless cannot change the system. What it does change is only the structure of the system. You won't get different traffic system simply by widening the highway from two to three lines in both directions. Similarly, you won't get hierarchy instead of anarchy, if the structure is multi-polar instead of bi-polar or vice versa.

Three previous structural characteristics were already mentioned by Waltz. What his theory of international politics is lacking is the interaction space, or what Wendt called microstructure of interactions. This interaction space represents a background on which interactions of agents occur. Take a transport infrastructure as an example. You have roads, railways, air corridors, and sea routes but you won't get the whole picture of the system, if you don't pay sufficient attention to terminals (i.e. intersections, seaports, airports etc.), where these agents (transport routes) get in touch with each other. And at the same time you actually need these agents to demonstrate some activity (here the action is cargo arriving by a ship, or train, or airplane) in order to know how interaction space facilitates agents' encounters. In case of international relations (and also my model) the interaction space includes two elements. The first one is related to geographical character of agents (states) and simply means that they are unable to move and that they interact within a spatial world in which they are positioned in relation to certain number of neighbors. This spatial world is in my model portrayed as a closed environment with each cell representing one state. As a consequence of closed character of the environment, cells at the one end of playing space are neighbors of those at the opposite one. Resulting shape is the easiest way how to formalize the real world of interconnected spherical Earth.

Yet there is also another element with respect to interaction space of international relations and since my model is a game theoretic one, this must be a payoff structure. As in the real world, actors in my model are functionally alike and anarchy is unalterable as well, but capabilities may shift greatly. If we don't want to end up with essentially static model/theory like that of Waltz, and if our intention is to enable change in the levels of capabilities as a result of states interactions rather than of their domestic particularities, we must define possible choices of agents and also outcomes of all their interactions. Interaction space as a payoff matrix of the game played by states does precisely that. It stands for a dynamic structural characteristic since it is tightly connected with interactions of agents (states) in which outcomes of players' actions depend also upon opponent's behavior. In game theory this is called strategic situation (Nicholson, 1992: 57). But at the same time any change in payoff matrix causes only structural modification of the environment, not change of the system itself, because interests and preferences of interacting players (states) are sometimes compatible, but on other occasions or in interactions with other actors they are not. Furthermore, they may even change during the game as in case of Czech Republic and Germany. Their interests as EU and NATO member states are compatible now in most of the cases, but that was hardly the case of Czechoslovakia and Nazi Germany in the 30s, or Czechoslovakia and West Germany during the Cold War. My goal in the following subchapter is to try to find the starting point of all interstate interactions from where they can gradually move either towards friendship or enmity.

3.3.1. Prisoner's Dilemma Payoffs

Every model is a simplification of reality focusing only upon the most important features. Here, the payoff structure does the same by trying to represent elementary form of agents' interactions. It consists of available choices of action of interacting players and it determines payoffs received after every possible outcome of the game. Payoffs stand for individual's ordered preferences over outcomes and rational agents choose from available choices of action so that they will maximize their utilities (this is at least the story of classical game theory). However, utilities of different players are basically incomparable and their symmetry, i.e. same payoffs for different actors if they get into similar situations, is more a mater of convenience that was skillfully utilized in agent-based modeling, than a well received scientific fact (see the whole relative/absolute gains debate). Thus we have four basic simplifications if we attempt to apply any payoff matrix on some segment of reality. They are: number of actors interacting with each other; number of available choices of action; ordering of actors' preferences; and symmetry of utilities that indirectly enables adding up of payoffs and comparison of players' success during the game.

In case of my model I assume pairwise interactions of players, who decide between two options (cooperation and defection) in the symmetric Prisoner's Dilemma game. I will deal with pairwise interactions later together with other *rules* governing who interacts with whom and how often. With respect to other three assumptions and in accordance with what Snidal has said, I will try to justify them theoretically as far as possible instead of inferring them inductively. This enables paying close attention to (shifts in) preferences and interests as different from outcomes, strategic calculations and particular actions (Snidal, 1985: 43). Hence, I don't want simply to pick up some payoff matrix and then to try to apply it upon as many real world examples as possible. I would like to do it the other way round. Analyze the reality theoretically and find the most suitable payoff matrix available.

The first simplification I want to deal with is the assumption of both players' binary choices between cooperation and defection. In game theory this common assumption causes little problem, but in international relations one can point out that there are many more shades of black and white. "The definition of cooperation and defection [in international politics] may be ambiguous." (Oye, 1985: 15) Only two options being at one's disposal may seem as too restrictive and not mirroring sufficiently the realities of the international relations system, where multilateralism and ambiguity often prevails. However, I agree with Downs, Rocke and Siverson (1986: 140), who in their analysis concerned with arms races declared that such a simplification "is useful in that it eliminates many unnecessary complications." Hopefully, this holds even for a more general level of interstate interactions as such and not only for arms races.

Yet there is another problem of what Snidal (see 1985: 46-47) called *interval-level payoffs*, and which can be understood in two different ways. On the one hand and in contrast to simple ordinal-level, interval payoffs are closely related to above mentioned comparability of individual actors' payoffs and their gradual adding up during the game. On the other hand, interval-level payoffs can also represent different degrees of cooperation. Many times, the key to dynamic changes in payoffs is variable investment (i.e. cooperation) ratio of particular player. Actor chooses not between simple cooperation and defection, but from different degrees of investment. Player can for example invest more after mutual cooperation, or less after mutual defection. Higher investment consequently offers greater reward, if opponent reciprocates, but also greater risk, if (s)he does not. Provided that resulting payoff matrix stays within the limits of one type of game (e.g. Chicken, or Deadlock) set at the beginning of the simulation, then interval-level payoffs understood as variable cooperation ratio provide only higher and more interesting dynamics, rather than radically different outcomes, when compared to consequences of simple binary choice between cooperation and defection. Moreover, I included in my model another mechanism securing variability of payoffs than that of different degrees of cooperation. The highly praised dynamics will thus not be impeded.

What seems more important is the preference ordering over four possible outcomes of interactions, in which two sides decide from two options giving thus rise to 2x2 payoff matrix. This order then determines what kind of game represents anarchic environment of international relations most properly. With respect to that I argue that it is actually the Prisoner's Dilemma payoff matrix that best corresponds to how states interact in anarchic environment. While making my point I proceed in several steps beginning with realism and Hobbes's theory of natural state, towards Michael Taylor's argument about identity of that natural state and the Prisoner's Dilemma, and closing the argument by stressing a difference between single-shot and repeated games as important factor when applying Hobbes and the Prisoner's Dilemma upon anarchic system of international relations.

Highlighting the links between realist ideas on the one hand, and Hobbesian natural state as a depiction of anarchy in international relations on the other, can be hardly seen as a radically innovative achievement of my model. Many scholars did this before. Following Knutsen's statement is just one example:

> Realist theories address the interstate system. Their key theoretical preoccupation is the old question of how order can be maintained in a system of sovereign states. The first modern theorist to address this question was Thomas Hobbes. He was one of the first theorists to make an explicit analogy between international interaction and the state of nature. This analogy has subsequently been elaborated by others, and is now a key image in realist theories. (Knutsen, 1997: 254)

Also Wendt described the common points of realism and Hobbes's writings (1999: 252) and similarly as Knutsen stated that "[A]lthough, there is no necessary connection between a Hobbesian anarchy and Realism, it is a natural link to assume" (Wendt, 1999: 259). Actually one of his three cultures of anarchy, the Hobbesian one, was explicitly linked to realist scholars and thinking (Wendt, 1999: 262-266), even though references to *Leviathan* were absent. So what is that natural state according to Hobbes that should mirror and also inspire the realist understanding of anarchic environment of states?

Best description of the state of nature as viewed by Hobbes and of international relations as viewed by realists is that they correspond to "war of every man against every man" (Hobbes, 1998: 85). But why so? First we must realize that in all men there is a "restless desire of power" (Hobbes, 1998: 66), which strongly resembles classical realism of Hans Morgenthau (1993: 5ff & 29). Furthermore and according to Hobbes, in condition of no supreme authority, there is no place for cooperation, no law or justice, and no means how to arbitrate between individuals desiring the same thing. For Hobbes, every man has only the right of nature to defend oneself as seen fit and thus at the end:

> there is no way for any man to secure himself, so reasonable, as anticipation; that is, by force, or wiles, to master the persons of all men he can, so long, till he see no other power great enough to endanger him: and this is no more than his own conservation requireth (1998: 83)

This is an exact match of what offensive realist Mearsheimer wrote about international politics (2003: 33-36). In such a state of universal war where "every man is enemy to every man" life is "solitary, poor, nasty, brutish, and short." (Hobbes, 1998: 84) Result of such a situation without any law-enforcing authority is what another realist Kenneth Waltz described with respect to international politics as a self-help system (1979: 91 & 105 & 118), where, to use the words of Hobbes, "every man will, and may lawfully rely on his own strength and art, for caution against all other men" (1998: 111). In fact Hobbes even pointed out that sovereigns (kings and parliaments of different countries) are precisely in such a state of nature as assumed to exist between men before the creation of government (1998: 85). All these factors, emphasis on power, lack of supreme authority, conflict of interests, and self-help principle, inspired generations of realist thinkers when pondering about anarchical environment of international relations.

Yet how can we formalize in game theoretic terms the Hobbesian state of nature that is similarly as the international relations system characterized by absence of government? Michael Taylor tried to do precisely that arguing that in:

> 'state of nature' men find themselves in a Prisoners' Dilemma; that is to say, Hobbes is assuming that the choices available to each man (or 'player') and the players' preferences amongst the possible outcomes are such that the game is a Prisoners' Dilemma; and the Prisoners' Dilemma is the *only* structure of utilities (out of a very large number of possibilities) which Hobbes *must* have assumed to obtain (1987: 129)

Following the argument of Taylor, we should first realize that the famous dictum of Hobbes that "covenants, without the sword, are but words" (1997: 111) implies not only absence of law enforcing authority but is also a key feature of all non-cooperative games including that of the Prisoner's Dilemma. In this game, mutual cooperation is collectively optimal solution but mutual defection is the only Nash equilibrium. Because no one can enforce cooperation, individual rationality leads players to defect, and hence receive lower payoffs than if they both cooperated. But this is just a restatement of what Hobbes said: “every man, ought to endeavor peace [cooperation], as far as he has hope of obtaining it; and when he cannot obtain it, that he may seek, and use, all helps, and advantages of war [defection]” (1997: 87). For Hobbes, peace is clearly better than war, but only government can provide it and that is the reason for people to create a commonwealth with a sovereign. Nevertheless, in anarchy the only rational action for him is war. Even though peace is impossible and war is necessary, there are still two other outcomes in the Prisoner’s Dilemma, namely unilateral defection and unilateral cooperation. With respect to them Hobbes wrote: “But if other men will not lay down their right [i.e. cooperate], as well as he; then there is no reason for any one, to divest himself of his: for that were to expose himself to prey” (1997: 87) and similarly: “he which performeth [cooperate] first, does but betray himself to his enemy; contrary to the right (he can never abandon) of defending his life, and means of living” (1997: 91). Thus we can say that based on Hobbes thinking, unilateral cooperation is even worse than mutual defection since the individual who cooperates in such a way in fact gives up without any resistance and therefore loses everything (s)he has. In a same manner unilateral defection must be better than the mutual one, since the other (cooperating) actor makes no effort to check the defecting player’s power. Finally, unilateral defection has to be also more beneficial than mutual cooperation, because otherwise there would be no need for sovereign to establish peace and enforce covenants since defection would not pay off anyway. To sum up the argument that was first provided by Michael Taylor, Hobbesian state of nature corresponds exactly to the Prisoner’s Dilemma order of payoffs, where unilateral defection is preferred to mutual cooperation, the latter one then to mutual defection, and the least popular outcome is unilateral cooperation.

Another problem, however, still remains. It is unclear whether Hobbes had in mind repeated, or only one-shot interactions of actors (men or countries), when he wrote his *Leviathan* (see Taylor, 1987: 134). The pessimistic outlook of his theory indicates the latter case, because it is the single-shot Prisoner’s Dilemma that makes cooperation impossible. On the other hand, Michael Taylor leans towards the former alternative. As with power and security dilemma (see the issue of proximate and ultimate goals above) an answer is maybe a bit more complicated. Most probably Hobbes understood that men and countries interact repeatedly, and there are even some hints pointing towards reciprocity in his writings. However, he was clearly unable to think of any other way of promoting peace and cooperation except for by a supreme authority of governing sovereign. This is fully understandable since he wrote *Leviathan* more than 300 years before Robert Axelrod proved the possibility of cooperation among egoist in the repeated Prisoner's Dilemma game even without sovereign. But the consequences of Hobbes's views were really unfortunate.

What was originally just a pessimistic conclusion of analysis of interactions (war of all against all in condition of no government), that was caused by at that time limited knowledge of the problem concerned, turned gradually into a priori realist assumption of inherently conflicting interests of states: "In short, realists view the world as one of constant competition for control over scarce goods" (this is the second of three core elements of realism according to Legro – Moravcsik, 1999: 14-15). This is of course part of the characterization of realism from the opponents' point of view, but one can hardly deny the plausibility of conflicting interests as a symptomatic feature of realist writings (Karásek, 2007: 12; if someone ever tried to deny that after all, see Feaver et al., 2000 with one exception of Wohlforth). Similarly, when Wendt assigned a role of *enemies* to actors in Hobbesian culture of anarchy that promotes above all relative gains concerns and worst-case scenario expectations, he was right in stating that this realist assumption must be "constituted by shared ideas, not by anarchy or human nature" (1999: 260 and also 262). Yet he was wrong in doing the same realist mistake of not seeing the 300 years old false conclusion of inevitable conflict that Hobbes draw from his analysis of anarchical environment (but see Fearon – Wendt, 2002: 64).

To use Schelling's terminology (1963: 83-89), games of pure conflict are zero-sum games, in which gains of one player are necessarily equal to losses of the opponent. On the other hand, the Prisoner's Dilemma is a nonzero-sum game with mixed motives of conflict and collaboration. Thus if interstate interactions correspond to the Prisoner's Dilemma matrix as shown above, then actors' interests cannot be purely antagonistic as realists (and Hobbes) tend to believe. Their mistaken pessimistic perception of anarchy as inevitably leading to conflict was caused by Hobbes's inability to see the possibility of cooperation among nations without supreme authority. But as far as his description of the natural state suits the Prisoner's Dilemma order of preferences, this bleak realist perception of anarchy is unjustified. Both conflict and cooperation are possible in such an environment thus making the Prisoner's Dilemma perfect starting point for emergence of amity and enmity.

None of that, however, answers the critique of agent-based modeling by realist scholars that turns attention towards relative gains and the way how payoffs are divided among interacting players. What Grieco (1988) actually challenged was the *neoliberal* contention about possibility of greater cooperation under anarchy (Keohane, 1984), but neoliberals in fact relied in large extent on the results of Axelrod's tournaments. When deriving their conclusions, both agent-based modeling and neoliberal theory used absolute gains concern that disregards other player's payoffs. Yet according to realists, the more conflicting and competitive is situation in the system, the more should players pay attention also to relative gains and the way how gains are split, so that present or future opponents would not become stronger.

This problem is closely related to commonly assumed payoffs symmetry in game theoretic models, because the same payoff for *both* players after mutual cooperation reasserts the existing balance of power if and only if both actors had the same initial capability level. If the interacting players had different power, payoffs symmetry causes their capability levels to be gradually adjusted bringing thus about change within the system at the level of distribution of capabilities and simultaneously enabling voluntary loss of power. Such a result directly contradicts assumed intention of states to maintain own position in the system and necessarily invites realist criticism from the position of relative gains concern. In the model I assume symmetric payoffs for both interacting players too, i.e. the same payoff matrix. In spite of realist objections, I argue that symmetry of payoffs is defensible generalization irrespective of relative or absolute gains concern (Halas, 2009). The crucial point is how we define relative gains and the sensitivity coefficient. Original formalization of relative gains paradoxically paid very little attention to power position of states in the system and, therefore, it asked for certain reformulation. The logic behind this reformulation required that if actor paid attention only to relative gains, its power position vis-à-vis interacting partner before and after the interaction must remained unchanged.

With respect to sensitivity coefficient that determines how important relative gains are, two power-related factors influencing it provide useful simplification of several neorealist hypotheses concerning impact of power upon relative gains concern. The first one says that the bigger is the *capability gap between two players*, the less they pay attention to relative gains when they interact with each other. This makes sense intuitively since marginal utility of additional unit of relative gain is decreasing with increasing power advantage over interacting partner and it can be inferred even from realist argument (Waltz 1979: 195). If there is very little competition between two parties (USA interacting with Vanuatu), absolute gains prevail. The second factor says that the better is your *position in the system*, the less you care about relative gains. Intuition behind the argument is simple again. The fewer states one has to fear, the less careful it is and thus also less attention it pays to relative gains. Argument can be inferred from what Waltz stated about large units altruistically acting for the sake of the system (1979: 198) and also from what Olson said about ”systematic tendency for ‘exploitation’ of the great by the small!” (1971: 29). Coefficient itself is then an average value of these two factors.

Now what is the effect of relative gains reformulation and sensitivity coefficient formalization? To show that symmetry of payoffs is a valid assumption consider common situation in which there are usually only very few great powers and the number of actors gradually increase as we descend on power ladder. All similarly powerful states would have the same first as well as the second factor and comparable capability levels would also cause that according to the first factor they would extensively care about relative gains in their interactions. This however means that similarly powerful states will receive similar payoffs. Now consider states with different power positions. If some tiny state interacts with great power, second factor says that it should care a lot about relative gains since there are plenty of other tiny states that it must protect from. It will therefore strive to gain as much as it can. In contrast, second factor in case of great power will be especially low because it has very few states to fear. Since the first factor would be low for both players because of the great capability gap between them, the great power would at the end necessarily care much less than its weaker opponent about gains it receives. Their gains would thus be much more similar than their power positions thanks to unlike sensitivity coefficient resulting precisely from greatly different power positions.

I showed the same on two real world examples of distribution of capabilities based on data from Correlates of War project (Halas, 2009: 47-51). Similarly, Christina Davis pointed in the same direction, when she wrote about unilateral concessions of the USA towards its weakened allies shortly after the WWII that contrasted with US demands for reciprocal adjustments from the 70s further on, when economies of Japan and Europe strengthened (2009: 178). What I argue for is that the assumption of symmetry of payoffs is a useful generalization that can be based even on realist thinking and that corresponds to reality fairly well too. Thereby I finished what was intended as a theoretical exploration of what payoff matrix corresponds to elementary form of interstate interactions. This part also closed the investigation of fourth structural characteristic, namely that of interaction space, and thus also of structure of the environment as such. What remains is to deal with non-structural factors in my model of the system of international relations.

3.3.2. Non-Structural Factors of the Environment (Noise)

Environment of international relations has, besides its structure, also non-structural characteristics that influence interactions of states. In my model I included two of them: misperception and misimplementation. They represent two distinct effects of noisy environment. The former represents mistaken interpretation of opponent's cooperation as defection, or vice versa. The latter stands for inaccurate execution of a given decision, when player defects instead of applying originally intended cooperation, or the other way round. Both of them are common human errors and can be of course well explained as unit level phenomena. For example man with a hard of hearing condition can understand and interpret sounds in a wrong way and person with dysgraphia is often unable to correctly put his/her thoughts on paper. Yet these individual idiosyncrasies are present only in some, not all agents. Probabilistic features of several behavioral strategies used by actors in my model can have very similar effect. What I am interested in are not unit level causes of players' mistakes, but those at the higher, systemic level.

Noisy environment in this model is a feature with comparable impact upon *all* players irrespective of their idiosyncratic differences. Unlike simple mistakes caused by *individual* deficiencies and imperfections, those caused by noise has their roots usually in complexity of the *environment*. As in the case when aggregate level of the morning rush hour noise makes it difficult to sleep next to the open bedroom window facing the main road or to focus on the work properly, so also immense number of information and interactions in the world renders perfect analysis and evaluation of situations by states impossible and often prevents players from achieving identity between intended and attained results. States and their leaders thus with certain low probability make mistakes too. By enabling both misimplementation of one's own decisions as well as misperception of opponent's behavior as two different effects of noise I try to improve realistic character of the model and increase its dynamics. Ability to determine "what others are doing and to make appropriate responses" is after all one of the four key factors influencing security dilemma and cooperation among states (Jervis, 1986: 62).

Without taking into account the possibility of falsely interpreting surrounding environment and opponent's behavior (on issue of perception in international politics see Jervis, 1976), or the small chance that our orders will not be duly carried out because of noise, it would be hard to offer a sufficient explanation of many important events in history. Impact of Soviet leadership's, or rather Stalin's cognitive closure, on situation in the first days after Nazi attack; shooting down of Korean airliner above the Sachalin peninsula; reasons for starting the second war in Iraq; or failure to pass advance Norwegian notice of coming rocket launch to relevant officers within Russian army, all these cases are examples of how information are sorted, analyzed, and used in decision making processes in noisy environment of international relations.

Yet similarly as elsewhere, we don't need to limit ourselves to great power interactions and worn out examples from the Cold War. On occasion of unveiling the statue of the first Hungarian king and saint, Stephen I, in August 2009, Hungarian president László Sólyom planned his private visit of Slovak border town Komárno, citizens of which are mostly ethnic Hungarians and whose former southern part on the other bank of Danube belongs to Hungary since Trianon. One can be fairly sure that president's intention was anything but to insult Slovaks, yet the unveiling ceremony was unfortunately arranged to take place on 21st August, i.e. on the very same day that people commemorate the anniversary of 1968 Warsaw Pact invasion of Czechoslovakia in which Hungary participated. Lack of appropriate information lead Hungarian side to expect that there would be no problems with the private visit, but the reality was different. Slovak government took it as an *intentional* insult and denied Sólyom (the president of neighboring country!) to cross the border bridge over Danube, an unprecedented step in situation when both countries are member states of the European Union. Stated in terms of the proposed model, lack of information caused that instead of being a low-profile private trip, Sólyom's visit misfired as a defective move that Slovaks moreover misperceived as intentional.

3.4. Rules

The last part of the international relations system, and of my model, that remains unexplained after finishing the portrayal of the environment few lines above are rules whose role according to Kaplan (1962: 13) is to describe relations within and between levels of the system. These very same rules as the third key element of all agent-based models Epstein and Axtell subdivided based on whether they govern relations between agents, between agents and environment, or between different aspects of environment (1996: 5). But it is also constructivism that stresses importance of rules:

> Rules make agents out of individual human beings by giving them opportunities to act upon the world … Through these acts, agents *make* the material world a social reality for themselves as human beings. (Onuf, 1998: 64)

The same of course hold for states as agents too. As in any social system, rules determine available choices and tell "agents which goals are the appropriate ones for them to pursue" (Onuf, 1998: 60). Rules are simply the link between different parts of the system that makes possible its functioning and dynamic development.

In previous sections of this chapter I paid a little bit more attention to argumentation of rationalist theories (neorealism, game theory etc.) than to constructivist reasoning. I will change that now. It is above all constructivism and its proponents, in contrast to rather static rationalism, that look at the international politics as on a dynamic process of mutual constitution of agents and environment (Wendt, 1999: 184; see also 1987). And rules are responsible precisely for that. Focusing upon rules, however, doesn't necessarily mean idealism:

> Constructivists do not deny the reality of the material world; they argue that the material world only has meaning within the context of social rules. A particular distribution of material capabilities cannot tell us much about world politics without knowing the dominant beliefs, norms and identities of the relevant agents. (Duffy – Frederking, 2009: 326)

In the following three sections I will try to define rules that shape international system, and control functioning of my model and its parts. Special emphasis will be laid upon how rules connect different parts of the model and how these linkages affect constitution, functioning, and interactions of agents as well as environment. Those three sections that ensue are in the following order dedicated to patterns of agents' interactions occurrence, behavioral strategies of states, and finally to development of (dis)trust among states via shift of mutual cooperation payoff. To what emergent phenomena (if any) this possibly leads is the subject of another chapter.

3.4.1. Interactions

Occurrence of interactions follows certain rules whose impact and form are usually greatly influenced by composition of the system. Imagine for example interactions within a family (the system) composed of multiple generations. Within each generation there is a parents-offspring relationship (structure of the system). Interaction within family would most probably follow two simple rules of occurrence. The bigger is the *age difference* and/or the smaller is the *relatedness* of any two members (units), the less often they would interact. These two rules related to *structure of the system* (family) causes stable *structure of interactions*, where siblings interact with each other more often than cousins, and offspring interact more often with parents than with grandparents. When trying to model a family, it is much easier to work with just two rules and apply them equally upon all agents instead of laboriously defining for each player individually how often and with whom (s)he might interact. The result is the same, but dynamics of the model is much higher, if we model structure of interactions from bottom-up with help of rules and not from top-down as a fixed structure. Similar rules governing the occurrence of agents' interactions in my model are examined here.

Five assumptions in my model relate to interactions' occurrence among states. They are repeated, dyadic, simultaneous, and any two players interact with each other depending on their power and distance. First three of them are rules regulating agent-agent contacts while the last two pay attention to agent-environment relations and take part even in Galtung's (1968) interpretation of the international relations system by means of small group theory. The easiest to deal is the assumption of repeated interactions. In the review of literature I already clarified the impact of iterations on the Prisoner's Dilemma game and on player's cooperation so there is no need to do that again. That repeated interactions between states commonly happen in the real world seems to be similarly obvious. In fact, states now rarely 'die' or are completely eliminated in case of war (see Waltz, 1979: 95 and Snidal, 1985: 51) and thus they have many opportunities to interact repeatedly. Although it wasn't always that way, since many times in history countries existed only for a brief periods (empire of Alexander) or disappeared after disastrous defeats (Carthage). Moreover, they were often separated by great distances with sparse population and little government that hindered direct interactions (Kievan Rus and China of Song dynasty). In spite of that, if the first interaction occurred, it very rarely remained unrepeated.

Another important rule that governs interactions is the assumption of dyadic interactions, which means that there will be only two sides/agents in all occurring interactions. Disregarding the fact that dyadic state relations are extremely popular in (statistical data) analysis of international politics (see e.g. Mesquita – Lalman, 1992: 16), there are some other reasons for using this particular rule:

> When discrimination is perfect, each state can adopt a separate policy toward every other state, and the N-person game can be analyzed as a set of linked two-person games. (Snidal, 1985: 53)

Public goods modeled as the N-person Prisoner's Dilemma has a defining character of being non-excludable, which means that you cannot effectively discriminate between participating players and prevent free-riders from enjoying the public good once it is created. Such a situation is unusual in international politics. States know with whom they are interacting and they are able to take different measures towards each other. For two sides in the Prisoner's Dilemma speaks also the fact that you have almost always only two sides in war (Jervis, 1997: 210-52; Galtung, 1968: 281-2). Nevertheless, alliances representing one of those two sides often exist in the real world and omitting them may seem as oversimplification. Possibility of alliance formation is undisputable but first, competition of alliances is most of the time just a continuation of individual states' rivalry on higher level without much difference in principle of functioning. And second, even if formation of alliances minimizes power competition among allies and thus also impact of security dilemma, it does not abolish it completely: "forming of two blocks … did not make the multipolar system into a bipolar one" (Waltz, 1979: 167). Greece and Turkey are both NATO member states yet their relations are anything but free from capabilities concern. Better way to deal with alliances is, therefore, to model relations of states in such a way that enables gradual diminution of the Prisoner's Dilemma by means of repeated mutual cooperation thus facilitating emergence of conditions similar to alliance creation and functioning. I did precisely that in my model as shown below in section dealing with payoff shift.

As regards interaction occurrence, two factors in my model determine whether particular dyad is activated or not. These factors are power and distance, and together with offensive capabilities and perceived intentions they define the extent of threat in Walt's theory replacing the simple balance of power concept. With respect to power: "[A]ll else being equal, the greater a state's total resources [i.e. aggregate power] …, the greater a potential threat it can pose to others." (Walt, 1994: 22) Importance of power hardly needs a stressing in international relations. Intuitive logic behind the way I formalize influence of power was perfectly expressed already more than 50 years ago:

> Big powers interact with great frequency, small powers with big powers but less so, and between the small powers there is very little interaction. (Galtung, 1968: 294)

First of the model's rules influencing occurrence of interactions thus assumes that the higher is the level of player's capabilities, the greater is also the probability of interactions with any other agent in the system. And since interactions are repeated as was already made clear above, capability level is thus necessarily the sum of gains from all previous interactions with all players. Interpreting presence of embassy as an alternative evidence of intense bilateral interaction, one can find a distinct pattern of relations influenced by distribution of power. There are 45 embassies in the capital of a small European country Slovakia. Fourteen out of the first fifteen biggest countries according to the strength of economy have their embassies in Bratislava, but none of the sixty economically least powerful states (see 2009 IMF data on GDP in purchasing power parity). Similarly, you can find Slovak embassies in all of the first 20 states with the most powerful economies, but you won't find any in the 60 economically smallest countries. Therefore it seems appropriate to link interaction occurrence with power.

The second factor influencing the probability of interaction occurrence in the model is geography or more precisely distance of agents. As emphasized by Walt: "[B]ecause the ability to project power declines with the distance, states that are nearby pose a greater threat than those that are far away." (1994: 23; for impact of distance on relative gains concern see Davis, 2009: 178) Kenneth Boulding pointed in the same direction long before Walt with his *loss-of-strength gradient* (1962) and Jervis picked up the problem of distance and geography as well by stressing that:

> "Even in today's international system, not all countries influence one another. A book on Afghan-Bolivian relations would be short … and few changes in the relations between Argentina and Brazil would affect anyone outside of the Western Hemisphere. (1997: 26)

Yet at least with respect to formal models and impact of location it is Lewis Fry Richardson (1960) that should be mentioned as a pioneer since he included in his model of arms race intuitive spatial assumption mirroring real world observation that: "All nations interact but with an intensity that decreases in geometric progression, with the increase of their separation measured around the equator." (1960: 174; for similar argument see also Galtung, 1968: 280) No wonder then that I formalize spatial factor in a way that the closer two agents (i.e. states) are, the bigger is the probability that they will interact. To see that this is actually a fitting generalization of how the real world works, take again an example of foreign representations. Six countries from Central Europe – Slovakia, Czech Republic, Poland, Hungary, Austria, and Germany –

represent a perfectly connected group in which every country has an embassy in all other states of the group. On the other hand, there are only three African embassies in Bratislava (only one from sub-Saharan Africa) and just four from America. Similarly, Slovakia has 5 foreign representations south of the Mediterranean and six across the Atlantic, compared to 33 in Europe. Geographic distance together with power thus makes a great difference as regards interaction occurrence. No wonder then that it caused a huge surprise when Caribbean island state of St. Kitts and Nevis decided to open its seventh embassy (only third in Europe besides those in London and Brussels) in Slovak capital Bratislava.

Two more issues concern interactions and their time patterns. One can model time either as continuous, when only some players interact and have their status updated in a given moment and thus there is no fixed unit of time in which all actors must act, or alternatively as discrete, when all players undergo updating and engage in interactions simultaneously in fixed intervals. The other issue is of simultaneous, alternating, or possibly even randomly alternating moves. In the first case, actors decide what to do at the same time. If moves alternate, players decides one after the other, i.e. one agent makes a choice first followed by the second player, and then again the first one etc. In the last case of randomly alternating moves, actors from a given dyad are picked up to make a decision (usually of investing in partner’s prosperity) in a haphazard manner. These issues are to great extent a matter of convention and operationalization, but there some other reasons influencing which options we choose as well.

First, in my model all players can theoretically interact with each other every single round, but power and distance variable cause that only some players and dyads are activated. Time is thus continuous rather than discrete. And second, with respect to non-simultaneous order of agents’ moves, there is a problem of necessity to define what can be regarded as cooperative move of investment in opponent’s welfare. There exist groups of bats whose members cooperate with each other by voluntarily feeding those members that were unlucky in finding a food (see Nowak – Sigmund, 1994: 219). Since every time different members get lucky during the search for food (obtaining in this way also an ability to ‘invest’ by sharing it), this can be a fine example of randomly alternating moves of agents. Yet what can be an investment in international relations? One can think of US generosity after the WWII, but as already stated this can be easily interpreted as tolerance towards disproportionate gains. Strictly speaking, in a game with (randomly) alternating moves the payoff received is not even strategically interdependent because what player gets depends solely upon opponent's decision. One can endlessly dispute whether Munich agreement and what followed was an example of mutual cooperation of four European powers, or naïve cooperation of France and Britain with deceiving defector exemplified by Nazi Germany, or betrayal (an apt reference to Czechoslovak description of agreement concerned as *dictate*) of cooperating Czechoslovakia by western powers, especially France. The most important fact is that the result was dependent upon action of both parties at the given moment. I therefore model the international relations system as the *simultaneous* Prisoner's Dilemma.

3.4.2. Strategies

In the Prisoner's Dilemma players can choose between cooperating and defecting move. However, in multi-agent simulations interactions are repeated, and thus agents play the Prisoner's Dilemma more than once. What makes actor to decide for cooperation or defection in these repeated interactions, that is what game theorist call behavioral rule or *strategy*. "Player i's strategy s_i is a rule that tells him which action to choose at each instant of the game, given his information set." (Rasmussen, 1989: 23) This "book of instructions" (Shubik, 1970: 183) can be either pure (deterministic) or mixed. Unlike in the former case, in the latter one the moves are prescribed only probabilistically. One can also categorize behavioral rules according to their level of conditionality. There are strategies that completely disregard previous rounds of interactions; there are those that have only limited memory with respect to time; and also those that focus only on opponent's moves instead of on the outcomes of interactions. Moreover, there can also be some mechanism for changing strategy during the game, which can cause important shifts in how population functions. For example players may learn from the experience and change the probabilities of cooperation and defection. Certain behavioral rules may be during the simulation even replaced by others, more successful ones. Thus besides usual psychological consistency assumption of given agent's behavior, which basically stands for using the same strategy in interactions with all partners, there are two other key issues. How to choose and formalize behavioral rules of actors, and what mechanism of strategy shift to include?

One strategy against all opponents does not mean that player makes the same move in a given round in all interactions with various actors. It simply means that (s)he uses the same behavioral rule in decision making process when (s)he engages various players with different histories of their previous interactions. The same rule may well possibly lead to cooperating move thanks to specific history of interactions (information set) with one opponent, or alternatively to defecting choice because of the completely different history of interactions with another player. What I assume is simply that state acts in the same manner when being in the same situations (information sets) and that whom a given state acts with doesn't matter *unless* their previous interactions were different. 'No negotiations' strategy applies to all terrorist groups irrespective of where they come from or what they try to achieve. Any inconsistencies in moves towards apparently similarly behaving opponents bring about strong public criticism as happened in case of US response to Iraqi and North Korean nuclear programs. Yet these two cases were at that time hardly analogous situations from President's administration (i.e. decision maker's) point of view, plus I have already dealt with the problem of perception. My point is also illustrated by the case of appeasement strategy that was discredited as an acknowledged foreign policy strategy after Munich agreement (see Ripsman – Levy, 2008). Again, if player took a lesson from Munich, (s)he would reject to appease universally in all comparable situations and not in a case by case ad hoc manner (Gilpin, 2002: 193). One strategy per player thus seems as a valid assumption.

In the single shot Prisoner's Dilemma there are only two possible strategies. In a repeated game with unknown number of iterations there is virtually infinite number of available strategies. So the obvious question is, what behavioral rules, and why, should be included in the model? As far as my intention is not to model specific foreign policies of particular countries, but rather to find if there are any emergent properties at the systemic level, the only requirement for population of strategies in this model is that it would be sufficiently heterogeneous. This on the one hand prevents possible generalizations from results of those simulations that were based on somehow bent input settings of the population, and on the other hand enables later comparison with results achieved via altered, different settings. Moreover, heterogeneous population of strategies is important with respect to any possible emergent property since we can be at least sure that there is no prevailing behavioral rule that directly caused this systemic phenomenon. Accordingly, I cannot think of anything in the international politics that suggests that all states use the same foreign policy strategy in their interactions. Countries balance, as well as bandwagon. They act to minimize threats, but sometimes they just ignore them.

Maybe more disputed then heterogeneity of population is how players change their behavioral rules (strategies). Various possibilities how to formalize evolutionary selection of more successful players or learning exist but I exclude any such mechanism since “the international system has neither the selective elimination (states are rarely eliminated even in war) nor the random variation that evolutionary theory requires” (Snidal, 1985: 51; see also Busch – Reinhardt, 1993: 436). Similarly, Paul Pierson pointed out that it is ”not that learning never occurs in politics. Rather, learning is very difficult and cannot be assumed to occur” (2000: 260). And what holds for domestic politics should do as well for the international one. Robert Gilpin argued in the same way that even if states were able to learn to be more enlightened and cooperative, it would still be no sure thing that they would actually do that.

> Although states (or rather the individuals who compose them and lead them) do learn lessons from their experiences, they do not always learn the same lessons, or what some might regard as the correct lessons. (2002: 227)

Thus it seems that neither evolutionary selection, nor learning, has any place in model of the international relations system. The most powerful states often disintegrate or simply lose their power as the 20th century Soviet Union, ancient Rome, or the 19th century Great Britain. If we understand fitness in terms of power (there is no available reproduction ratio), then the fittest does not necessarily survive in international relations. Progress via conscious learning or imitation is doubtful as well. Some strategy may be successful in one environment, but lead to great failure in others. Strict balancing worked perfectly well in the 18th century Europe, but it won’t if applied in the 21st century by the member states of the European Union.

Yet Alexander Wendt (1999: 318-335) wrote about identity formation of sovereign states through evolutionary processes of natural and cultural selection, the latter being further subdivided into imitation and social learning. What I stated above holds particularly for his concepts of natural selection and imitation. I disregard any such mechanisms because of lacking empirical validity. At the same time, (unintentionally) *becoming* more cooperative/defective is one of the ways how to understand payoffs shift in my model that I want to describe and explain in the following subsection. These shifts as I formalized them correspond fairly well to what Wendt dubbed *social learning*, and with help of which Alter and Ego can mutually (re)create their respective identities. Importantly, this process of social learning, possibly exemplified by payoff shifts, is more a matter of gradual, unintended, and mutually constitutive modification of perception, interests, and identities, rather than of copying other player's strategy or intentional alternation of one's own behavior because of previous experience.

Moreover, with respect to evolutionary processes, there is actually a kind of interactions preference in the proposed model, since the most successful players (i.e. those with the highest accumulated gains) will interact mainly with other prosperous actors. This resembles an evolutionary situation, in which successful players thanks to higher reproduction ratios meet a greater number of similar actors in the next generations. However, here the numbers of well performing strategies won't increase as happens in properly formalized evolutionary development.

3.4.3. Payoffs Shift

In preceding sections I identified the international relations system with the Prisoner's Dilemma game, which may seem as a universal fixed claim about nature of states' interactions. Yet Fearon and Wendt warned us to be careful while making such assumptions about functioning of the world. They focused particularly upon realist understanding of anarchy as inherently self-help, competitive, and conflict-prone environment, and emphasized that there is always a danger that:

> through a process of forgetting what we are doing, what starts out as merely an analytical convenience can become something more than that, a tacit assumption about what the world is really like which limits our theoretical and/or political horizons. The assumption that states are self-interested, for example, is harmless when made as an analytical convenience, but if turned into a tacit universal claim it can lead us to conclude mistakenly, that anarchic systems are necessarily self-help worlds rather than contingently so in particular historical circumstances. (Fearon – Wendt, 2002: 64)

This warning holds for my model as well and thus I need to avoid any similar a priori prevention of changes in players' understanding and perception of their environment and themselves. Instead, what I want to do is to show that anarchic system of Prisoner's Dilemma as modeled in my thesis can change in a way that offers possibility for different cultures of anarchy to evolve similarly as has been suggested by Wendt (1992).

While introducing mechanism responsible for changes in the meaning of anarchy, I draw my inspiration from constructivist understanding of the way how agents and structure mutually shape each other, and from how this constitutive interdependence is (re)produced via social practices (Wendt, 1987). Here, the agents are states, structure is the Prisoner's Dilemma payoff matrix, and social practices are particular actions that players take in repeated dyadic interactions. These social practices (cooperation or defection) then "continually produce and reproduce conceptions of Self and Other" (Wendt, 1999: 36) characterized here by roles of enemy or friend as the third level of international cultural environment (Jepperson – Wendt – Katzenstein, 1996: 34; see also Wendt, 1994: 390 for how cooperative interactions can lead to collective identity formation). To say it differently, repeated actions of interacting players can:

> greatly reduce uncertainty among actors within a socially structured community, thereby increasing confidence that what actions one takes will be followed by certain consequences and responses from others (Hopf, 1998: 178)

as in the case of relations between friends and enemies. At the same time, the longer the same social practice lasts the stronger and more stable is the cultural effects it leads to (Wendt, 1999: 311) or else "The higher the level of trust or distrust, the lower its flexibility." (Jervis, 1976: 195) Same cooperative/defective action used repeatedly diminishes uncertainty inherent in anarchic nature of international relations system and enables actors to create expectations about future behavior of the opponent. Repeated defective moves of either player would make particular relationship more conflict prone thus leading to culture of enmity, distrust, and suspicion. On the other hand, repeated mutual cooperation makes agents trust each other, and expect even more cooperation in the future, thus creating gradually culture of friendship and amity. As already stated elsewhere: "past interactions may affect present behavior, perhaps by increasing interdependence or by changing expectations and *trust* among nations" (Snidal, 1985: 49 emphasis added; for early experiments with trust and suspicion in the Prisoner's Dilemma see Deutsch, 1958). In my model this happens by making the Prisoner's Dilemma (as a structural feature) more, or alternatively less, challenging via payoff shift caused by individual action of players.

Shift of payoffs within certain limits as a result of players' interactions is an assumption trying to mirror constructivist argument about "equal weight [given] to agency and structure. They are *mutual*ly constitutive and codetermined." (Wendt, 1999: 184) In case of the model presented here, payoff matrix shifts towards coordination game of Assurance (also called Stag Hunt) or Deadlock according to pattern of players' interactions, and this amended structural variable of interaction space then in reverse influences how actors behave, how they perceive each other, and what they see as their best interest (for shifts between various games see Snidal, 1991: 707-8). On the first page of the second chapter I described the order of payoffs in the Prisoner's Dilemma. In Deadlock this order is changed into T > P > R > S and Assurance game must fulfill the condition R > T > P > S. These games represent two extremities towards which the reward payoff in my matrix can gradually move closer and closer.

To use the distinction between two types of game theory, payoff shift is an example of its *holist* version, where structure of the game is understood "as shared knowledge that constitutes agents with certain identities and interests." (Wendt, 1999: 183) Continuous mutual cooperation of a given dyad gradually increases possible reward of these players from their future interactions and brings this payoff closer to that for unilateral defection (temptation). Hence the Prisoner's Dilemma becomes less threatening, more similar to Assurance game, and the prospects for cooperation are in effect enhanced similarly as among friends or allies.

> Prisoner's Dilemmas in which the payoffs for CC are relatively high and those for CD, DC, and DD are relatively low are more likely to yield cooperative solutions. In other words, cooperation is more probable when mutual cooperation is only slightly less attractive than exploiting the other (Jervis, 1986: 64; see 76 for shifting estimates of others' behavior)

Contrariwise, (continuous) defection by at least one party in dyadic interactions necessarily increases suspiciousness of players, which leads towards perception of the opponent as an enemy. I formalize that as gradual decrease of gains (reward) for mutual cooperation towards punishment payoff. The Prisoner's Dilemma becomes increasingly challenging and similar to Deadlock game as viewed for example by Germans in the 30s or Soviets from the late 40s (see Downs – Rocke – Siverson, 1986: 120-123).

Players' actions thus change the structural feature of interaction space, which in return influences expected gains (and utility) from actors' future encounters and thus also their behavior. Moreover, since term *identity* "(by convention) references mutually constructed and evolving images of self and other" (Jepperson – Wendt – Katzenstein, 1996: 59), changing interaction space also mirrors the way how two players understand identity of each other. Shifts in reward payoff thus represent dynamic cultural relations of amity and enmity with associated features of trust and suspicion as well as corresponding expectations as regards opponent's behavior. Previous behavior in my model shifts present payoffs and present payoffs alter interests and identities of actors that guide their future behavior. Agents repetitive performance, i.e. defection or mutual cooperation, alters structure (payoff matrix) and structure retrospectively alters agents since the more (or less) beneficial is the mutual cooperation (reward), the less (or more) acute is the Prisoner's Dilemma that helps define both them and their interests in iterated dyadic interactions.

With respect to alliance functioning and formation, trust-building behavior of gradual overcoming of dilemma concerned is the best way how to model path towards institutionalized collective defense, when actors cease to perceive other states as threats and start to regard their behavior as cooperative and mutually beneficial. The intuitive logic behind the concept is inspired by the fact that the higher degree of cooperation particular actors demonstrate in their interactions, the more they trust each other, because they feel they know each other, the other's nature, and that the other actor is behaving predictably. Even cultural argument of political communities relies on that to certain extent (Deutsch et al. 1969). An example of such institutionalized alliance is NATO, whose 40 years of anti-Soviet cooperation created such a level of trust and common identity of friendship that enabled its continuation even after the Warsaw Pact dissolution. On the other hand, alliances in the 17th and 18th century Europe never lasted for long because shifting behavior of individual states never allowed for the sufficient diminution of the Prisoner's Dilemma, emergence of trust, and necessary institutionalization.

These repeated practices of cooperation (or defection) also create a kind of cushion that enables ignoring occasional inconsistencies in patterns of behavior caused either by noisy environment, or even by intentional shifts as determined by some probing strategies. Thus long-lasting and intense mutual cooperation of Czechs and Slovaks creates such a level of trust between these nations that readily overcomes even such events as dissolution of Czechoslovakia, or international problems with the level of democracy as happened to Slovakia in the late 90s. What a difference compared to cautious Slovak-Hungarian relations, where even such a remote issue as Kosovo independence is perceived by Slovak leadership as having a possible negative impact upon future of this relationship. Another example of (dis)trust building and shifts between amity and enmity caused by repeated practices are relations between France and Germany before and after the early 50s, or between the Soviet Union and the United States before and after the WWII. Thus in words of Alexander Wendt:

> Bipolarity among friends is one thing, among enemies quite another. The one might be an "Assurance Game," the other "Deadlock." (1999: 107; see 109 for how history matters)

As already stated, I regard Hobbes's natural state describing anarchy among agents in absence of sovereign as fitting, succinct, and basically identical with the Prisoner's Dilemma game and with the situation of states in international relations system. On the other hand, I stressed that conclusion about impossibility of cooperation he derived from his analysis is mistaken and that realists unfortunately accepted this pessimistic conclusion as a necessary result of anarchic environment. I don't see the need for such an a priori assumption with respect to the Prisoner's Dilemma and system of states. Quite the contrary, my understanding of the game is much closer to what Lars Udehn said about Hobbes's description of natural state:

> The most conspicuous feature of the state of nature is the lack of society and of culture. … His [Hobbes's] theory of the social contract stands out as a first paradigm of an individualistic explanation of social order. (2002: 481)

For me the Hobbes's natural state, and thus also the Prisoner's Dilemma, is an empty box of mixed motives game. A structural feature to be filled in by the actions/practices of agents. It enables emergence of both enmity and amity, but does not make any of them inevitable. It is a dilemma precisely because it makes possible both conflict and cooperation. From this Hobbesian point of departure without society or culture, one can move with help of repeated practices either towards enmity or friendship. It is Deadlock with generally prevailing conflicting relations that better exemplifies culture of enmity. And it is Assurance game with its cooperative Nash equilibrium that is more intuitive formalization of culture of friendship. The Prisoner's Dilemma or anarchy is the starting neutral point from where we can get closer to enmity as well amity depending upon pattern of repeated interactions.

After finishing the description of rules as the last of three key elements of the proposed design besides agents and environment, I believe I successfully answered all questions raised at the end of the previous chapter. The model includes theoretically justified assumptions about the frequency and the basic form of interstate interactions. It presents some arguments as regards progress in international relations, identity of actors, their ability to properly evaluate complex environment, as well as those concerning implementation of their own decisions. The next chapter must then inevitably explore methodological questions related to this model including problems of operationalization, scientific added value and innovativeness, as well as issue of research questions.

4. Methods and Operationalization

Computer simulations as a quantitative methodological stance taken in this thesis and multi-agent simulations as a specific method used for data acquisition are together with problems of the proposed model's operationalization subject of this chapter. After short opening on (non)linear relations, I first proceed to cope with abductive inference and consequences of complexity for research in social sciences. Subsequent application of abduction upon multi-agent simulations is followed by a section specifying questions I would like to find answers to in my thesis, and the final clarification of how various parameters described in the previous chapter were operationalized in the program. There are of course other possible simulation methods, or rather techniques, as for example cellular automata, multilevel simulations, queuing models, or microsimulations (see Gilbert – Troitzsch, 2005: 13), but multi-agent simulations is the best way how to put into praxis agent-based models of complex systems, which I would like to show now.

Qualitative methods and case studies approach are generally considered as being especially suitable for explaining complex phenomena and getting the whole and satisfactory picture of various problems in international relations. That is because they are often looking at only very few cases with lots of considered variables (Bennett – Elman, 2007: 171). On the other hand, quantitative methods try to explain as many cases as possible with help of the fewest possible assumptions while at the same time (statistically) identifying key variables that stands behind linear relationships between explanans and explanandum. Special kind of quantitative methodology based on relatively recent developments in computer science and called multi-agent simulations is, however, quite distinct method well suited precisely for the analysis of complex systems and emergent phenomena. It falls within a family of quantitative research methods because simulations are capable of generating great amount of measurable and easily replicable data.

Complex system means that outcome(s) and/or functioning of such an entity, and thus of course of associated agent-based model, is not determinable by force of pure logic, deduction, or mathematical inference (Axelrod, 1997: 3), which partly explains the adjective of the closely related *emergent* phenomena. This type of models contain many autonomous actors, stochastic variables, multiple possible initial states, feedback loops, and highly interdependent features that render impossible usual forms of insight such as mathematics or statistical probability analysis.

> One of the themes of social simulation research is that even when agents are programmed with very simple rules, the behaviour of the agents considered together can turn out to be extremely complex [i.e. nonlinear]. Conventional statistical methods for analyzing social systems are almost all based on the assumption of a linear relationship between variables. That is, the effect on the dependent variable is proportional to a sum of a set of independent variables. (Gilbert – Troitzsch, 2005: 10)

Usually, neither simple causal relations between inputs and outputs, nor easily identifiable (in)dependent variables can be found in agent-based models and in related complex systems. On the other hand, their complex nonlinear relations can be readily replicated via multi-agent computer simulations (Axelrod, 1997: 3). Repeated interactions of their autonomous agents often lead to intended or unintended emergent properties at the higher, systemic level of the model concerned. That's also why one can often draw a clear cut distinction between equation-based mathematical or statistical approaches to scientific modeling, and their agent-based counterparts (Parunak – Savit – Riolo, 1998). In other words:

> There is often no set of equations that can be solved to predict the characteristics of the system. The only generally effective way of exploring nonlinear behaviour is to simulate it by building a model and then running the simulation (Gilbert – Troitzsch, 2005: 10)

As I said, this method is capable of generating large amount of data. Running the simulations is exactly the way how it is done, which makes us aware of another peculiarity of a given approach.

4.1. Computer Simulations of Complex Social Systems

By repeated runs of the program with option to vary input parameters, computer simulations make possible experiment-like research design, which is unseen and unprecedented in social sciences (Gilbert – Troitzsch, 2005: 4). When compared to rather rigid nature of statistical analysis, this quantitative research method enables us to get a better grasp of *dynamic* functioning of any complex system (also called *target*; in my case it is the international relations system and the emergent phenomenon of cooperation within it). Moreover, via inclusion of feedback loops it facilitates formalization and better understanding of constitutive relationship between agents and structure. Or in other words, it explores linkages between micro- and macro-level properties (see Gilbert – Troitzsch, 2005: 13). But besides obvious advantages multi-agent simulation method necessarily entails also several drawbacks.

Precisely thanks to the nature of complex systems in the social world, above mentioned experiments rarely lead to discovery of one way relationships and similarly accurate knowledge as in the natural sciences. I'm not saying that there are no feedback loops and mutual shaping of agents and structure present in problems that natural sciences deal with. But the sheer fact that social world composed of individual human beings actually functions thanks to mind-dependent (i.e. language-dependent, i.e. socially-dependent) non-observables makes social sciences more interested in exploring agent-structure interdependence and constitutive instead of causal relations. Logical consistency understood in terms of deductive reasoning would be fine, but unlike in natural sciences, you cannot always take social world for granted and deductively infer predictions from general assumption expecting to be able to test them whenever you want under the same conditions. We have basically no influence over mind-independent natural phenomena, but the very existence of objects of inquiry in social sciences is in the end necessarily dependent on human (i.e. observer's) action. Under normal atmospheric pressure, 100 °C will be the boiling point of water regardless of whether we have concepts to describe such a discovery or make use of it. On the other hand, arguably the last witch in Slovakia was burned similarly as in the rest of Europe in middle 18th century in 1741. Nowadays there are none, and this is not a case like that of human caused extinction of moa or dodo. People just ceased to act accordingly.

Even better knowledge of some complex social system needs not necessarily mean greater capability to predict its future development since you usually don't have the opportunity to gather data via real-world experiments and compare them with simulation outcomes in order to calibrate the model (see Tesfatsion, 2006: 845).

> the best one can do is to test that there is a reasonable likelihood that the observed behaviour of the target could be drawn from the distribution of outputs from the model – which is rather a weak test. (Gilbert – Troitzsch, 2005: 212)

For example in natural sciences, you can make a computer simulation of a wind tunnel's airflow past the new airplane's wing, then build the plane itself, and finally try, if it actually flies. Similarly you can model avalanche occurrence in a given valley, then arrange avalanche barriers, and see if they work. If real world events do not correspond to simulation results, you can calibrate the input variables and move on. There is usually no such option in a complex social world. You can model international relations system, but you cannot experiment with the real one, or built an alternative to it. So in case of your simulation results being different from actual behavior of the target (and of course, given there is no large N of comparable targets), you basically cannot decide whether it is your model that is flawed, or simply that what you observe in actual world is just an accidental development of otherwise completely differently evolving system. Moreover, prediction based on outcomes of simulations comes forth only if the model offers very accurate picture of the modeled target. Precisely because of the dynamics and complexity of the social world we almost generally lack sufficiently comprehensive knowledge of complex social systems to achieve this level of accuracy (see Gilbert – Troitzsch, 2005: 23 & 18-19 for highly abstract models' validation problems).

Hence if not causality, accuracy, and ensuing testable prediction, then we must simply opt for understanding and higher level of abstraction (Macy – Willer, 2002: 146-7; Gilbert – Troitzsch, 2005: 26; Simon, 1996: 16). Yet here we come across another peculiar issue in international relations theory namely the possibility of objective knowledge. Observer and observed are inseparable in social sciences.

> [T]here are two plausible stories to tell, one from outside about the human part of the natural world and the other from inside a separate social real. One seeks to explain, the other to understand. (Hollis – Smith, 1991: 6)

Explanation makes sense only if we accept the possibility of objective knowledge, identification of (in)dependent variables, and centrality of causal reasoning, which is fairly unproblematic within rationalism. I wrote that prediction and explanation are difficult, but there is still the other epistemological option emphasizing subjective understanding of the world instead of objective causal explanation (Hollis – Smith, 1991; see Wendt, 1999 for a bit different view on relation of epistemology to ontology). Proponents of this approach are often labeled as interpretativists or reflectivists, and contrasted with rationalists (Keohane, 1988). The problem is that it would be a bit overstretched argument, if we included multi-agent simulations into the group of interpretative qualitative methods. Scholars might be right when they stress possible lack of predictive power of the method I decided to use. But to choose 'understanding' (Axelrod, 1997; Gilbert – Troitzsch, 2005) as the only alternative option that remains available after rejecting explanation and prediction is a rather questionable and misleading decision. It only discloses unawareness of the debate on epistemological issues in international relations theory, and maybe also still unsettled terminology of the research program based on multi-agent simulations of complex systems.

If we disregard those ends of computer simulation methodology that relates to training of some skills (flight simulators) or entertainment (Xbox, PlayStation), we basically end up either with prediction, or its alternative in form of the urge to better grasp some insufficiently explored phenomena. In case prediction is for whatever reason unattainable, then *exploration* rather than *understanding* seems to be a better term for what multi-agent simulations can achieve. And even more so with respect to established terminology of international relations theory. Social complexity of the modeled target often disables identification of causality or application of hypothetico-deductive model of science. But although there are feedback loops, possibility of modeling constitutive relations, as well as partial departure from methodological individualism of rationalist approaches, researchers dealing with agent-based models do not limit themselves to interpretive methods. Multi-agent simulations do generate measurable data. It is a quantitative method, even if a special one. Thus if my goal is *exploring* the functioning of the international relations system, it must necessarily represent a third option besides inadequate understanding and unattainable explaining.

Anyway, I am not going to develop any third epistemological position. I just believe that similarly as in ontological matters, where agent-based modeling embraced parts of substantive rationalism as well as constructivism, so also in case of epistemology and methodology the multi-agent simulations of agent-based models take middle position between quantitative and interpretive qualitative approaches in order to explore how complex systems work. In spite of all that was mentioned above, one thing nevertheless still remains true, and that is the fact that agent-based modeling and related method of multi-agent simulations:

> is not only a valuable technique for exploring models that are not mathematically tractable; it is also a wonderful way to study problems that bridge disciplinary boundaries (Axelrod, 2006: 1568).

This particular kind of computer simulation as a data generating technique, moreover, cannot be associated with some specific theoretical position or school. But it is true that methodological individualism of the classical game theory enabled effective application of multi-agent simulations upon complex systems research problems, and this in turn caused that many do make a strong connection between them. My own model itself does contain many features adopted from game theory, but it tries to go beyond individualism and clear separation of actors and structure.

I decided to use this method because of its proven ability to grow emergent phenomena from interactions of agents, who are then influenced by the very same systemic consequences of their own actions. Despite some of its drawbacks, this method enables generation of large amount of replicable, quantifiable data, and thus makes up for lacking real world experiments. That helps us explore functioning of complex systems, and under specific circumstances even propose their perfection in a desired way. In fact, I regard simulation methodology as the best possible option for any attempt to think about systemic level of international relations. And especially so together with agent-based modeling approach. Available qualitative and quantitative methods turned out to be of rather limited benefit when dealing with similar complex systems anyway. But before I point out possible scientific benefits of the proposed model and specify the questions I would like to find answers to in my thesis, I first set it all within the framework of abductive inference accommodated for the purposes of multi-agent simulations of agent-based models.

4.2. Abductive Reasoning

The whole agent-based enterprise seems to start in a usual deductive manner by constructing a model with help of general assumptions about composition and ruling principles of the target. Yet in the next step computer simulation research does not compare predictions inferred from these general assumptions with information acquired by observing the real world. Instead, it generates own data via simulations and subsequently makes inductive generalizations from these data upon functioning of the modeled target. Thus, some view the multi-agent simulations and agent-based modeling as the “third way of doing science” besides widely accepted deductive and inductive ways of inferring hypothesis (Axelrod, 1997: 3-4). Basically, if we find some complex phenomenon or a system in the real world that we need to or want to understand better, but cannot because of missing data or (in case there are available data) of lacking analytical tools, then we construct an agent-based model and run the associated multi-agent simulations. The data we get should help us explore our research problem.

Actually, in addition to deductive and inductive reasoning there really is a third option well suited for agent-based modeling. It is called *abductive reasoning* and was developed by Charles Peirce, who regarded it as the only method truly generating new ideas (see 1994: 2.96 & 5.145; in early writings he even dubbed it *hypothesis*, *retroduction*, or alternatively *presumption*). Some scholars from our field of study called it even a "pragmatic research strategy" and argued that:

> abduction should be at the center of our methodological efforts while deduction and induction are important but auxiliary tools. Abduction follows the predicament that (social) science is, or should be, above all a more conscious and systematic version of the way by which humans have learned to solve problems and generate knowledge in their everyday lives. (Friedrichs – Kratochwil, 2009: 709-10)

According to Peirce himself, who understood the scientific process in terms of unity of all three types of inferential reasoning, abduction generates new hypothesis, deduction draws predictions, and induction puts them under test (Peirce, 1994: 5.171 & 7.218).

However, abduction raised serious doubts among scholars mostly because of the way Peirce described it (see e.g. Kapitan, 1992; but also Hoffmann, 1999). On the one hand, he declared that "abduction is, after all, nothing but guessing" (Peirce, 1994: 7.219), and that "[n]o reason whatsoever can be given for it, as far as I can discover; and it needs no reason, since it merely offers suggestions." (1994: 5.171) Yet on the other hand, he made sure that abduction "is logical inference, asserting its conclusion only problematically or conjecturally, it is true, but nevertheless having a perfectly definite logical form." (Peirce, 1994: 5.188) He defined abduction in the following way:

> The surprising fact, C, is observed;
> But if A were true, C would be a matter of course,
> Hence, there is reason to suspect that A is true.
> (1994: 5.189; see also 2.623)

Yet there are problems concerning what kind of hypothesis we choose, as well as why we choose it? Relationship between two premises of the abduction is the most contested issue and Peirce unfortunately remained rather vague with respect to that. For him, coming up with hypothesis is a matter of insight and some background knowledge. Understandably, this is not enough to put abduction on a par with deduction and induction. Insight does not prevent us from proposing the most foolish hypothesis. Even if Peirce tried to introduce some preference ordering into the set of possible hypotheses, his attempts were regarded as insufficient, if not counterproductive. For him:

> The abductive suggestion comes to us like a flash. It is an act of *insight*, although of extremely fallible insight. It is true that the different elements of the hypothesis *were in our minds before*; but it is the idea of putting together what we had never before dreamed of putting together which flashes the new suggestion before our contemplation. (Peirce, 1994: 5.181.3 emphasis added)

Objections thus remained (Kapitan, 1992). In what way do we infer A from C, and why should we prefer it, if there are probably many other available hypotheses?

Yet despite all skepticism, people do make abductive inferences. They regularly propose hypotheses explaining observed data and then proceed to test them after drawing predictions as Peirce demanded. You do not have to watch *Dr. House* to realize that diagnostics is abductive process par excellence, when physicians try to find out what is the explanation of patient's problems, so that they would be able to cure him/her. Similarly, reasoning of William of Baskerville from *The Name of the Rose* by Umberto Eco is a perfect example of the inference, which is non-reducible to deduction or induction. Again, this is not obvious from Peirce's above mentioned definition, but while trying to find out what constitutes a good abduction, he instantly shifted without a sign of hesitation or stopping to the problem of good *explanation* (1994: 5.197). His implicit emphasis upon explanatory power of hypotheses then enabled later perfection of his concept of abductive inference.

Today abduction is generally identified with its refined and better developed version called *inference to the best explanation* (Harman, 1965; Lipton, 2004), which seems to solve problems of both what hypothesis we draw from available data, and why we prefer that particular hypothesis. Although Lipton understood inference to the best explanation as a guiding principle of *inductive* rather than abductive reasoning, his extremely broad definition of induction actually included all non-demonstrative reasons (2004: 5) as opposed to those that deductively ensure true conclusions given true premises. Moreover, he cited Peirce as well as Harman as authors that already before him analyzed the issue he was concerned with (Lipton, 2004: 56-57). Therefore, I will use abduction as an alternative name for inference to the best explanation even if Lipton recognized only deductive and inductive reasoning.

Now, to shed some light on abductive problems of description (what hypothesis) and preference (why this hypothesis) as articulated by Kapitan but also Lipton, let's start with "the idea that explanatory considerations are an important guide to inference, that we work out what to infer from our evidence by thinking about what would explain that evidence" (Lipton, 2004: ix). One can already see the double connection to Peirce's theory via both emphasis on explanation, and inference of hypothesis from given evidence. For understanding Lipton's theory, it is furthermore important to notice the difference between inference and explanation. Take an example of four seasons. Since we observe winter, spring, summer, and autumn in the Central Europe each year, we use inductive generalization to infer that they will continue to alternate also in the future. Yet this inference does not explain *why* they actually change. To get an explanation of changing seasons one needs to know obliquity of the Earth as well as its orbital motion around the Sun. Bearing in mind the difference between inference and explanation, Lipton defines abduction in a following way:

> we infer the explanations precisely because they would, if true, explain the phenomena. Of course, there is always more than one possible explanation for any phenomenon … so we cannot infer something simply because it is a possible explanation. It must somehow be the best of competing explanations. … Given our data and our background beliefs, we infer what would if true, provide the best of the competing explanations we can generate of those data … Far from explanation only coming on the scene after the inferential work is done, the core idea of Inference to the Best Explanation is that explanatory considerations are a guide to inference. (2004: 56)

Obviously this is a much more developed version of abduction than that offered by Peirce. We infer the best possible explanation given available information (the ‘what’ question), and then we assume that this inference is true, because it is actually the best available explanation (the ‘why’ question). Harman (1965: 89) basically described inference to the best explanation in the same manner as Lipton, and Josephson with Josephson (1996) then finally formalized it in a similar way like Peirce did before.

Nevertheless, there still remain some questions especially with respect to quality of being the best explanation. Lipton tried to make clear what he meant by defining ‘best’ in terms of *the loveliest* potential explanation, which in turn means such a hypothesis that provides deepest understanding of available data (2004: 61). Of course, not even that is a very specific. Therefore he points to the so called *contrastive explanation* as a tool that helps us choose between different explanations and find the best one via comparing assumed causal stories: “To explain why P rather than Q, we must cite a causal difference between P and not-Q, consisting of a cause of P and the absence of corresponding event in the case of non-Q” (Lipton, 2004: 42). Moreover, explanation must also demonstrate features of simplicity, unification, and theoretical elegance (Lipton, 2004: 68) to be considered ‘lovely’. Being simpler, more plausible, and able to explain more in a less ad hoc manner, these are criteria for judging one hypothesis better than the other also for Harman (1965: 89). Yet not all of this is possible to apply upon agent-based modeling of complex social systems. Exploration rather than explanation is the best term for what multi-agent simulations enable. Next section shows how to use abduction in context of complex social systems.

4.3. Evaluating Research on Social Complex Systems

At the first sight, there should be no problem evaluating relevancy and rigor of scientific theories and related research with help of established criteria. But the problem is that the best known scholars that deal with the assessment of scientific value of different research questions in international relations have adopted critical rationalist view that promotes hypothetico-deductive model of science with deductive inference of predictions from theoretical axioms/hypotheses, and subsequent need for their empirical falsifiability (see Popper, 2002). Thus besides generally required originality, Walt (1999) also demands deductive logical consistency and empirical validity, and a book by King, Keohane, and Verba (1994) is very similar with respect to that too. However, given what I wrote about observer-observed relationship, possibility of real world experiments, causality, and stability of social phenomena, it seems that the hypothetico-deductive model of enquiry and demands for logical consistency and empirical validity are not always compatible within social science of complex systems.

Taking world of natural sciences for granted, (wo)man can easily start her/his research in a deductive way by making theoretical hypothesis, drawing predictions, and then falsifying or corroborating them against evidence exactly as Popper demanded. Of course, some social phenomena are more stable than the others, and I am certainly not trying to say that deductive reasoning is something foreign to social sciences. Yet as far as multi-agent simulations of complex social systems are concerned, the real world (experimental) data testing of predictions is rarely achieved or even expressed as a goal. With respect to my inquiry into the problems of computer simulations of complex social systems and given the fact that natural phenomena are independent of human mind, but social ones are not, there must be a difference between the ways how social and natural sciences do their job. Modeling of social complex systems as a scientific enterprise functions in a different way than natural sciences do. Application of the hypothetico-deductive model is at best a bonus, rather than the core of computer simulations.

Abductive reasoning is much better suited for social science agent-based modeling and the related computer simulation methodology than is the case of its deductive counterpart. At least as far as artificial intelligence is concerned, this has been noticed by other scholars as well (Josephson – Josephson, 1996). We simply cannot take world of social sciences for granted, and thus we have to start with accurate observation assuring that the unexplored object of our research actually still exists. Otherwise it would be of concern only for historians. Given that the phenomenon exists and is significant, which is obviously rather arbitrary, one can proceed to build a model. Plausible and in the best case scenario also empirically valid assumptions of the agent-based model should together with replicable multi-agent simulations enable us to grow the modeled phenomena. If this is achieved, one can as the final step conclude that it is reasonable to regard assumptions of the model as correct, thus successfully exploring functioning of the complex system. No need for, and possibility of, real world experiments and deduction so far.

Only thereafter, we may try to inductively (from simulation results) or deductively (from model's assumptions) infer some predictions with respect to the real world, and examine if they really hold by manipulating particular features of the target. There are for example both deductive and inductive ways of inferring consequences of noise for cooperation of actors as shown in the review chapter and (wo)man can test them by eliminating noise via improving access to information (common role of institutions). If our inferences prove to be wrong, then either our hypothesis (assumptions of the model) is wrong, or there is a possibility of multiple outcomes. In the former case, one is supposing causal-like relations, which is not always appropriate within complex systems. In the latter case, one needs to conduct more real world experiments and better statistical analysis, neither of which is always possible as well.

With respect to the original definition of abduction by Peirce (1994: 5.189) it is then possible to propose a reformulation for the purposes of agent-based modeling:

> An unexplored emergent phenomenon of some complex system is observed;
> agent-based model of corresponding complex system is constructed;
> if multi-agent simulations lead to growing of the emergent phenomena;
> then there is a reason to suspect that assumptions of the model are correct.

As one can see, similarly as in Peirce's writings, one proceeds from given evidence or observations to formulation of new hypothesis (model), which if successful with respect to simulating the target then justifies abductive inference about its correctness. Yet as in the case of Peirce's original definition, modified version of abduction fitted for agent-based modeling call for more precise description of the way how we move between premises of the argument, i.e. of the way how we get from observation/evidence to particular form of the hypothesis. Furthermore, one needs to make sense of what has to be done after we formulate the model itself. Is there any place for deduction and induction as Peirce contended, or do we just have to forget about any empirical data?

Criteria for evaluating research in social sciences can help us greatly with respect to previous questions. Above I tried to show that generally accepted criteria for considering some social science research to be good are not very helpful here. Nevertheless, we can still draw some inspiration from them and refine these rules according to the logic of inference to the best explanation. I argue that requirements any good agent-based research has to meet include real world and scientific significance, (intuitive) plausibility of assumptions, and replicable data. The first characteristic of every sound agent-based model using computer simulations that I would like to focus on is the significance both with respect to real world and to the scientific community as well. Not only were these aspects of significance already expressed by King, Keohane, and Verba, but this criterion in fact also includes Walt's 'originality' condition.

> Ideally, all research projects in the social sciences should satisfy two criteria. First, *a research project should pose a question that is "important" in the real world.* The topic should be consequential for political, social, or economic life, for understanding something that significantly affects many people's lives, or for understanding and predicting events that might be harmful or beneficial … Second, *a research project should make a specific contribution to an identifiable scholarly literature by increasing our collective ability to construct verified scientific explanations of some aspect of the world.* (King – Keohane – Verba, 1994: 15 emphasis in original)

The second feature of every good agent-based research is the plausibility of its assumptions, which is also a kind of shortcut for applying inference to the best explanation upon agent-based modeling and thus also for deciding which of the possible model's compositions counts as the best exploratory tool for a given complex system. Plausibility can be achieved theoretically or empirically, but ideally via both ways simultaneously. Necessity to empirically and analytically justify different proposed features successfully limits the number of possible alternative models since it is hard to defend movement of actors across the playing grid, if you try to model system of states.

However, you can still include many additional features or modify the present ones so that the model will correspond better to the real world target. What to include and what to left behind is an important issue related to the question of model's plausibility (Gilbert – Troitzsch, 2005: 19). One has to strike a compromise between maximizing accuracy and simplicity in order to get the loveliest model with the highest exploratory power. At the one end of the continuum there are usually highly complicated models with many details and internal characteristics of agents included. They commonly represent what Lipton called ‘likeliness’, and they attempt to produce an accurate copy of the modeled complex system, thus heightening the probability of desired results (emergent phenomena). The problem is that many features of such a model have none or only very little impact upon simulation results and hence could be omitted altogether. Allocation of resources, territorial growth, ethnic composition of population, regime change, all these features are probably redundant if you model the international relations system. Notice also that loveliness and likeliness are not necessarily disjunctive properties in case of inference to the best explanation (Lipton, 2004), because lovely model can also be the most likely to produce appropriate results.

At the other end of the above mentioned continuum there are exceedingly abstract models with only very few assumption (Axelrod, 1980a). If successful in growing the emergent phenomena, they can offer exploratory qualities of unmatched loveliness. But many times, great abstraction comes on account of empirical and theoretical plausibility. You can hardly justify assumption of round-robin interactions in the international relations system even if it is the simplest possible pattern of interactions. Deciding what to include in agent-based model requires striking a balance between simplicity and accuracy by asking in a Lipton’s way ‘Why this feature rather than the other?’ In order to maximize model’s loveliness in form of theoretical elegance, unification, and simplicity (Lipton, 2004: 68), one must thus always keep in mind overall empirical and theoretical plausibility.

Finally, for every sound research it should be a matter of fact, that if the model built upon plausible assumptions leads towards successful growing of the modeled phenomenon, then related simulation results must also be readily replicable as the third condition of good research requires (see Axelrod, 2003). But the problem of replicability defined broadly has several aspects besides that of ability to reproduce data by other members of scientific community. To prove that results are not artifacts, first and foremost one must be sure that they are not caused by some bug in the source code. Nevertheless, being preceded by definition of the puzzle, observation of the target, and construction of the model, debugging is only the fourth out of six key steps of every modeling research design (Gilbert – Troitzsch, 2005: 19; see the right side of Figure 3 below). Initial two correspond to the first premise of the abductive inference as defined above, while the third one is identical with its second phase. It ensures that more or less

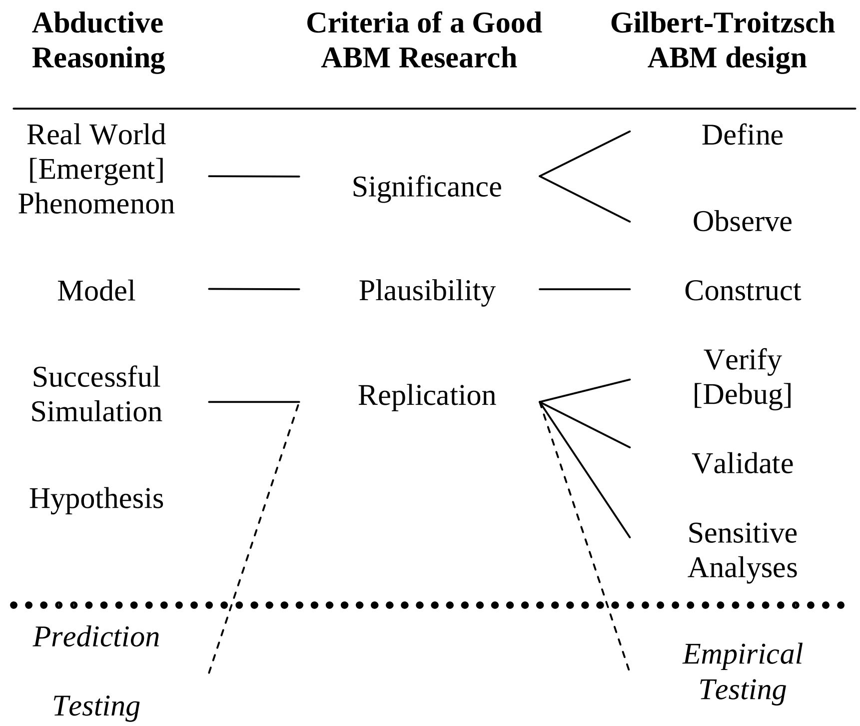

Figure 3: Template for Agent-Based Modeling of Complex Systems.

abstract assumptions of the model elicit the sense of intuitive plausibility even in a layman. The fifth step, which Gilbert and Troitzsch called ‘validation’, aims at securing the match between outcomes of simulations and functioning of the target, and together with the fourth (debugging) and sixth step (sensitivity analysis) it fits nicely within the third line of abduction’s definition, which attempts to evaluate model-target correspondence. These last three steps also find their place within broadly defined replication criteria of a good multi-agent simulation research.

I already said a lot about problems of acquiring relevant real world data on social complex systems. Predictions are rare, experiments are impossible, and small number of comparable cases together with complicated nature of relations prevents proper statistical analysis. Requiring empirical tests as part of the replication criteria thus seems many times unrealistic. Yet I also wrote that I would try to apply abductive reasoning upon agent-based modeling of complex systems. And Peirce expected that after provisionally accepting the hypothesis abductively inferred from available empirical evidence research will proceed by way of deduction “to trace out its necessary and probable experiential consequences” (Peirce, 1994: 7.203). This would prepare the ground for testing of predicted outcomes and measuring “the degree of concordance of that theory with fact” (Peirce, 1994: 5.145). Similarly, Lipton stressed the possibility:

> to use Inference to the Best Explanation to infer from the data to a high level theory, and then use the consequence condition to deduce a lower level hypothesis from it. … The clearest cases of the consequence condition, however, are deduced predictions. (2004: 63)

Not all agent-based models are equally complex and, therefore, there can actually be some chance for making deductive inferences. Few studies mentioned in the review of literature and dealing with effects of noise can illustrate that (Bendor – Kramer – Swistak, 1996: 334-335; Bendor, 1993). But even if deduction is unavailable, one can still turn to sensitivity analysis and inductive generalization.

Considering the best possible scenario of plausibly constructed model, whose simulation results accurately mirror targeted phenomena (remember that this correspondence can still be accidental), then the most one can do in case of many models with respect to their real world similarity is really only to conduct sensitivity analysis as the sixth step of Gilbert-Troitzsch design. By manipulating input parameters of individual reruns of the program one can try to isolate their impact upon simulation outcomes, infer real world consequences, and subsequently recommend modifications (if possible) of those parts of the real world target that might change functioning of this modeled complex system in a desired way. Then, if results of these modifications are different from what has been expected, one either has to change assumptions of the model, or run more simulations in order to explore undiscovered end states. This is probably the only way how to build a weak but at least some non-trivial data link between the model and the target.

4.4. Research Questions

The question or rather problem that drives my research is *whether properties of the international relations system enable and facilitate success of cooperative behavior, or alternatively if such a success is just a matter of chance?* I don't ask if there is any cooperation or possibility of it, since there obviously is. The issue is rather whether the situation we observe is just an accidental event, or alternatively a necessary outcome of a given system. To use a distinction between various traditions of methodological individualism as interpreted by Lars Udehn (2002), I would simply like to know, if cultureless Hobbesian state of nature exemplified by the Prisoner's Dilemma payoff matrix leads towards some kind of spontaneous order as described by Adam Smith and possibly represented by repeated mutual cooperation and associated payoff shift. If not, then adverse conditions can cause existing cooperation to disappear without great chances of being established ever again. But if there is some push towards cooperative spontaneous order, even if in form of only unstable equilibrium, then recurring disruptions will be probably overcame by reestablished cooperation at the end. And we will only need a proper ratchet to minimize effects of such disruptions.

Before proceeding to specify additional issues I would like to examine in this thesis, and before describing particular features of the operationalization, it is necessary to look at my research from the perspective of criteria evaluating its added value. Thesis deals with the international relations system and with cooperation in it. Whether states have to wage wars, or are instead encouraged to cooperate, relates to all the people's lives, so there is hardly any doubt of real world importance. Model should improve our understanding of stability of cooperation and provide us with insights into probable evolution of the system of international relations. That might enable us to prepare for future events and to prevent occurrence of some of those that can disrupt cooperation. Exploring the nature of the system turns international environment more legible for practical politics thus making it better equipped to deal with new situations.

Similarly with respect to scientific significance and scholarly literature (King – Keohane – Verba, 1994: 16-17; Walt, 1999: 12-13), this thesis fulfills stated requirements as well. Proposed model contributes to theoretical thinking about international relations by trying to unite features of different schools within a single framework. In the previous chapter you could find several attempts to reconcile rationalism and constructivism, and to solve the absolute/relative gains problem. Design of the model also combines and further develops various elements already present in different agent-based models, but not yet joined together under the common roof with a specific intention to mirror the international relations system. For me this fact represents the greatest added value of my model. Moreover, there are some features presented in a radically new form unexamined within the literature and not applied in the Prisoner's Dilemma models so far (payoff shift, occurrence of interactions etc.). All that may already secure the necessary scientific significance of the proposed model.

Yet there is one more fact contributing to the scientific importance of my research and that is an attempt to rerun Axelrod's second tournament and compare its outcomes with results of the proposed model (comparability is secured above all by using the same set of strategies). I consider it here under significance criteria because it concerns replication *of* somebody else's research rather than enabling replication of one's own research *by* somebody else, which of course relates to the third evaluative criteria. Axelrod himself (2003) stressed the importance of replicating results published by other scientists as a kind of self-check by the discipline itself (one of the very few examples is Axtell et al., 1996). By way of replicating results of already existing models one can easily reexamine their validity and robustness both under original and modified settings. But Axelrod realized the problems resulting from low availability of source codes and limited space for description of models in scientific journals (2003). How I coped with these problems is shown in subchapter dealing with operationalization.

Resemblance between crucial characteristics of the model and those of the real world system is besides theoretical justification one of two pivotal requirements of the plausibility criterion as applied upon agent-based scientific research. All the features included in my model are in fact intended to secure its realistic nature and thus to avoid objections to the insufficient relevancy for the real world. High empirical plausibility of model's assumed properties serves as a link between the goal of exploration of the international relations system and results of computer simulations. Understandably, I tried to base all assumptions in my model on at least some empirical grounds and/or to justify them analytically. Hence even though the main argument for using the Prisoner's Dilemma game was theoretical, its general applicability underlines that too. Assumption of distance between actors as a factor influencing occurrence of interactions similarly demonstrates strong empirical basis, and payoff shift as the third example has both theoretical as well as empirical foundations. The same holds for all other assumptions of the model. As a consequence of the way how the proposed model was constructed, its overall dynamics will be greatly enhanced compared to predecessors, and the similarity with real world environment will be unparalleled despite inevitable simplification. Whether the model is also lovely or not, is at the end only upon the reader.

As regards ability to replicate results of my simulations *by* other scholars, I ensure this in three different ways. First, later part of this chapter explains in a detailed manner how I operationalized variables proposed in the model of the international relations system. Second, source code of the computer program that made simulations possible will be enclosed to this thesis. And third, all the data generated with help of repeated reruns of the program with various settings of input variables will be available as well. With respect to what Gilbert and Troitzsch (2005) called verification, and which I placed within the third evaluative criteria because of its key role for replication, with respect to all that I hope I did my best and got rid of all bugs in the code. But I postpone proper elaboration of this debugging step of research design until I deal with the operationalization of variables themselves and writing the source code as such, i.e. till we know what to debug.

The last, but not always attainable part of broadly defined replication criteria of a good agent-based research is empirical testing. To be clear, modeling behavior of specific states facing each other in some particular situation was definitely not my goal.

> The real power of game theory, for both empirical and theoretical purposes, emerges when it is used to generate new findings and understandings rather than to reconstruct individual situations. (Snidal, 1985: 27)

The real world guide for construction of my model was not some spatiotemporally limited case study as for example arms race before the WWI, or the Cuban Missile Crisis. Instead, empirical plausibility of model's assumptions that mirror systemic characteristics is meant to facilitate inductive generalization from simulation outcomes towards consequences of international politics as regards evolution and stabilization of cooperation among states. The purpose is not to model some particular case, but rather to enable interpreting and seeing the events in international politics through lenses of those expected consequences. Yet testing these inductive generalizations either with respect to past developments, or possible future modifications of the real world system, is unfortunately beyond the scope of this thesis. While in other research designs empirical work only starts after formulation of predictions, in case of agent-based models and multi-agent simulations this is similarly as here often the end.

Now what are the specific research questions besides the general one, which was stated above? First, given declared attempt to rerun Axelrod's second tournament, I would like to examine robustness of his results and success of TFT strategy. Second, given outcomes of previous models and presence of cooperation in the international relations system, conducted simulations should lead to similarly cooperative pattern of interactions, at least if the proposed model is realistic enough. Thus I would like to know what share of overall interactions (of the winner and also in the system) would end with a mutually cooperative outcome and how would it be influenced by changing simulation parameters. Third, apart from the question of what particular strategy would be victorious under various circumstances, I am maybe even more interested in what are the properties of prosperous strategies. Would they be more generous than strict reciprocators (this is what I expect), and if yes then how much? Or would it be excessive retaliation that would secure success? Does it play any role whether the rule is deterministic, or probabilistic? Accumulated gains as a proxy for prosperity together with the share of mutually cooperative outcomes enable us furthermore to isolate the impact of various input settings and variable parameters upon evolution of cooperation in the system and upon success of particular (types of) strategies. Finally, if we consider dependence of interaction occurrence on power position of actors, i.e. situation when the most powerful players interact also most frequently and especially so with other powerful players, then it seems intuitive that simulations may lead towards some kind of scale-free or small-world network. Emergent topology is an important issue since such a structure of interactions in the system of international relations would have significant consequences for stability of cooperation within it. All this because scale-free and small-world networks can better overcome loss of individual cooperative nodes and prevent spreading of defective behavior than the simple von Neumann or Moore neighborhoods. Forasmuch as this is the last item on the list of problems I would like to examine with respect to cooperative tendencies in the international relations system, I can now proceed to deal with the operationalization of the model.

4.5. Operationalization

To successfully move from description of proposed characteristics of the model of international system to multi-agent simulations themselves, one must necessarily translate rather vaguely stated ideas into precise form of some computer program. If we stick to the 'prototypical specification' of spatial agent-based models (Dibble, 2006: 1517) then besides agents, environment, and various rules governing their interactions one must also pay attention to initial conditions at the start of the game, to the timing of various processes during the simulation, as well as to the way how generated data are stored and processed. All that will be dealt with in this subchapter.

As Gilbert and Troitzsch pointed out (2005: 21), one can either try to write his own computer program from scratch, or to choose an easier option and use some already existing platform with available libraries (for their review see Railsback – Lytinen – Jackson, 2006). If researcher decides or ends up writing his own code as happened in my case, "a question then arises about the best programming language to use" (Gilbert – Troitzsch, 2005: 21). Luckily, there exists one type of languages that makes programming of multi-agent simulations more effective:

> Contemporary object-oriented programming (OOP) languages are particularly natural ones for agent-based modeling. Objects are structures

> that hold both data and procedures. Both agents and environmental sites are naturally implemented as objects. The agent's data fields (its instance variables) represent its internal states (for example, sex, age, wealth). The agent's procedures (methods) are the agent's rules of behavior (for example, eating, trading). This encapsulation of internal states and rules is a defining characteristic of OOP and greatly facilitates the construction of agent-based models. (Epstein, – Axtell, 1996: 5)

First, by creating class of objects scientist defines what attributes (data variables and methods) are common to all members of that particular class. For example in my program all objects representing individual countries are members of a general class called '*states'* and must be able to store own capability level, spatial position, outcomes of previous interactions, and they must also use some decision-making method, which is actually their strategy ascribed to them at the beginning of each simulation. Second, objects as autonomous *instances* of some class have to be initialized by loading a simulation per se. Noticing the similarity between autonomous objects and independent agents, it makes perfect sense ”that nearly all multi-agent simulations are written using object-oriented programming languages” (Gilbert – Troitzsch, 2005: 181). These are for example Java, C#, Visual Basic, or the latest versions of Fortran. Writing the whole source code in C# is in my case a perfect example of path dependence effects of accidental circumstances. I had very little or no knowledge of agent-based modeling, multi-agent simulations, and object-oriented programming, when I started to learn C#. At that time, studying new language seemed to me as difficult as trying to understand functioning of any of the available platforms and since I was able to acquire the 2008 edition of Microsoft Visual Studio development environment for free, I opted for C#.

4.5.1. Debugging, Baseline Models, and Graphical User Interface

Before portraying the way how I formalized individual variables of the model, let me say few words about starting, running, and repeating the simulations. One of the key steps of multi-agent simulations of agent-based models is verifying that there are no bugs in the source code. And as already mentioned above, this search for errors in the program is also an inseparable part of the process aimed to secure that our own results are replicable by other scholars. Then the best way how to verify the source code "is to re-implement the model using a different programming language" (Gilbert – Troitzsch, 2005: 212). That is exactly what I did with respect to the largest part of the code, where all strategies are formalized. Although Axelrod's second tournament was done more than 30 years ago, Fortran 77 in which it was written is an easily understandable language. Therefore I was able to translate all his strategies into my C# code. Besides facilitating the goal of replicating Axelrod's results, such a translation of the code from one language into the other represents a great opportunity to check whether your new program is written correctly or not, since any errors would only widen the gap between original and replicated results.

However, problems can arise even from the old source code. Articles published in scientific journals generally contain only very brief description of the model, and just a sample of generated results usually already in form of statistical analysis. In such a situation you need to revive and rerun the old program in order to get data you would be able to compare with outcomes of your own translated source code. Yet Axelrod made public only the code that formalized second tournament's strategies, and not the rest of it that determined exactly how actors interacted. Three problems appeared. First, because of the missing part of the code, I had to rely on written description of the model published in a journal article (Axelrod, 1980b). Yet editing of the article was not perfect as exemplified by the missing number of repetitions in the fourth run of simulations (Axelrod, 1980b: 383). Second, according to the same article 63 strategies were presumably paired in 3969 different ways (63 x 63). That is not true. Even if we allow for repetitions in form of interactions with oneself, one can combine 63 rules in only 2016 unique ways. Since we lack detailed information about how the tournament was conducted, it is possible that interactions of many pairs were computed twice with maybe different outcomes each time thanks to probabilistic nature of several strategies included in the original model. And finally, during the reviving process of the old Fortran code (wo)man needs to use so called *compiler* that executes given program. Compiler used by Axelrod is no longer available, so I tried to use Intel Visual Fortran Compiler (version 11.1.035) that seemed most capable of coping with the original source code. But for whatever reason, and even after discussion with Fortran specialist Ladislav Hanyk from the Faculty of Mathematics and Physics of the Charles University, this compiler was unable to execute some of the multiple consecutive IF statements present in several strategies of the program (other compilers were even less successful). Debugging via translating the code from one language into the other was therefore far from unproblematic. While trying to compare results of both codes, I thus had to rely on insufficiently detailed results as they appeared in the published article (Axelrod, 1980b).

Although debugging via translation proved at the end extremely helpful, there are several other strategies for verifying the program (for general discussion see

Axelrod, 1997: 210-214; Gilbert – Terna, 2000: 69ff). "Test everything" is just one of it (Dibble, 2006: 1541). According to that principle you should try to isolate and check every change you have made to the code and every rule you have introduced, in order to see if their consequences corresponds to the expectations under controlled conditions. This seems to be an extremely time consuming advice to follow given approximately 4500 lines of code in my program, but at the end it can help to avoid even greater waste of time spent in search for some hidden bug. However, besides using inbuilt Visual Studio debugger and fully relying on it with respect to solving any possible floating point difficulties (Polhill – Izquierdo – Gotts, 2006), I chose a bit different strategy of verification than that of *testing everything*. I did try to verify many features in isolation, but most importantly, after finishing the program I reviewed all the strategies one by one again, comparing their functioning in the translated and the original source code. I actually even found some bugs in the Axelrod's code but more on that later.

Axelrod's model with all its features then understandably represented one of two so called *baseline models* for my research and I used it both for debugging, and also for enhancing scientific significance of my research via attempted replication.

> The baseline model can be designed to be the equivalent of a null hypothesis in statistical analysis: a model which is not expected to show the phenomenon in question. Then if an addition to the baseline model is made, and the model behaves differently, one can be sure that it is the addition which is having the effect. (Gilbert – Troitzsch, 2005: 201)

My second baseline model, which I have introduced only after successfully replicating Axelrod's second tournament, served as a null hypothesis per se and thanks to its features also as an intermediary crucial for comparing results of the proposed model with those of Axelrod. In this second baseline model I used all 63 original strategies of the second tournament (later I use only 62 unique second tournament rules since two of the 63 were identical), the same payoff matrix as Axelrod did, and most importantly round-robin pattern of interactions.

> Even models that seek to understand the effects of spatial or other interaction structures should be able to run a spatial control simulations where the same set of agents interacts in a null space … in order to distinguish the effects of agent or other model specifications from the effects of their interaction structure. (Dibble, 2006: 1517-1518)

But on the other hand, I added into this second baseline model additional strategies that proved successful in other Prisoner's Dilemma models, and disabled interactions with oneself. I also computed outcomes of every round of interactions for both members of the pair at the same time and run each simulation for the same number of 10 000 iterations as in the full version of my model instead of averaging 5 reruns with different lengths like Axelrod did. By doing this and only subsequently complicating the model by additional features like payoff shift, noise, or power-proximity determination of interaction occurrence I was be able to find out what impact had all these features upon results of multi-agent simulations.

The last thing I would like to mention before turning to formalization of model's individual features is the graphical user interface (GUI). Older models usually existed just in form of computer programs that were compiled by a compiler and researcher often got only the final results (this was also the case of Axelrod's tournaments). Any change of settings required change of the source code. Recently developed multi-agent simulation platforms represent great progress since they already enable to quickly modify input settings by way of various check boxes, spinners, and buttons. That is also the reason why I built the GUI for my own program as well.

After loading an executable file that starts the application, researcher can in the main window of the GUI determine initial settings of subsequent simulation. These variables includes number of actors, level of both kinds of noise, payoff matrix, speed of payoff shift, initial power level, and the pattern of interactions (round-robin or power and/or proximity dependent). In another window one then chooses, what strategies to include in her/his experiments. Running the simulation in still another window is quite simple and user always knows the iterations count, overall sum of gains for each player, as well as who is currently winning the game. After finishing or interrupting the simulation, researcher can save the outcomes, and reset initial setting before starting another rerun. I also tried to make the GUI as user friendly as possible. Besides *Help* item in a menu bar that offers specification of the program's functioning, there is a button that checks if payoff matrix corresponds to the Prisoner's Dilemma, and another one that resets the matrix to original values used by Axelrod. User can also easily redistribute strategies on a playing grid or change them individually by rewriting numbers shown in the corresponding table. Finally, written description of all strategies can be displayed in the same window where these behavioral rules are selected, and before starting the simulation or after interrupting it one can also examine whether the interaction of any particular two players would occur in the next round, or not.

4.5.2. Agents and Environment

Some features of the model present very little problem during the coding process, while others are more complicated. In general, agents and environment pose comparably less difficulties than principles governing their mutual interactions, or corresponding rules of behavior. We strive for heterogeneity across simulations in order to avoid results that would be caused by accidental circumstances and this heterogeneity is secured by many agents, different haphazardly distributed strategies, multiple simulation runs, many random variables, and probabilistic interaction occurrence. Thus for heterogeneity you need both quantity and variability. If some stable pattern appears out of such a model, robustness of acquired results would be considerable. Yet securing conditions that enable heterogeneity is much easier with respect to the rule of numbers than in case of variability. Creating dozens of the exactly same agents is not a big deal. Environmental variables are a bit more complicated since they can have different consequences even under similar circumstances especially if they are probabilistic, but they are applied upon all objects in the same way. Random numbers, timing, and noise belong to those features that are easier to formalize, while interaction occurrence is a bit harder nut to crack. True complications then arise only from formalizing the set of various strategies.

Not only many strategies, but also all probabilistic features like computation of noise and interaction occurrence require generating random numbers out of the interval from 0 to 1. As recommended by others (Dibble, 2006: 1521-22), I picked up new value from this interval every time I needed to use a random number. With respect to timing, power levels of all states were simultaneously updated after each round. Since not all pairs are activated in every round anyway, continuous updating would be of dubious added value, if not even distorting results thanks to the influence upon average capability level. Finally, players suffered from both kinds of noise, but unlike in case of misperception, the fact that agent misimplemented his/her own decision became necessarily known immediately afterwards in the next round, so that the actors using particular strategies (e.g. CTFT) would be able to correct this type of mistakes. It also required little modification of some of the Axelrod's behavioral rules (without impact upon the logic of their decision-making), because few of them saved their last move similarly like strategy called APPOLD at the time of decision, not at the time of execution. Such a formalization would have basically hindered correction of own implementation mistakes. On the other hand, automatically revealing the fact that (s)he misperceived opponent's behavior makes very little sense and there is no need for that.

Outcomes of the game are dependent upon actions of both players and those actions in reverse depend upon choices made with help of the previous experience (maybe except in case of RANDOM rule). If one does something different than (s)he decided to, the outcome will change and the player will inevitably note that expectations and results do not meet. This holds as far as one does not misperceive the final outcome of interaction at the same time. In that case, however, player has little opportunity to find out immediately that (s)he is deceiving himself/herself. Of course, there are learning strategies and various averaging mechanisms that can minimize effect of such a mistake. And many players applied them in one way or the other. Yet this is a matter of individual effort and not of systemic tendency. Simply stated, one can compare own intentions with the reality of what has been done. But there is no alternative reality, somehow more real than the one we individually perceive, with which we could compare our views and definitely say, that yes this is really real. We don't see into the minds of others, and we cannot get out our own. Everything we can do is to try to approach "the truth" yet we can never grasp it perfectly. We can only constantly develop better learning strategies, but without the possibility of ultimately and forever deciding what is the only one correct perception. It might all sound a bit complicated, but it is as plain as the fact that if either misperception or misconduct occurs, it is not undone in the future as a matter of course. The effects might be corrected by individual actors but do not have to.

To get back to actors themselves, they are same in their capacities to store and process data, but because they have been given variously complicated strategies, they can be vastly different with respect to how they use this capacity. After baseline models using number of actors equal to number of different strategies, the full model works with 100 independent actors (4950 unique pairs), which should provide a sufficiently large environment for desired heterogeneity. Since the pool of available strategies is smaller than the extent of population, certain amount of actors corresponding to the difference between these two numbers will use behavioral rule already present in the population. However, no strategy will appear more times in a given simulation than is the nearest integer greater than the ratio of population size to the strategy set. Number of actors is determined by the size of closed squared lattice (i.e. toroid) representing a playing grid. As a consequence of closed character of the environment, cells at the edge of the playing grid are neighbors of those at the opposite one. One can imagine many other ways how to model territorial character of players, yet the toroidal shape is arguably the most common spatial environment in agent-based models and also the easiest way how to formalize the real world of interconnected spherical Earth.

There are 10 rows and 10 columns in this environment and each player has 4 immediate neighbors. If we consider the fact that every sovereign state in the real world has in average approximately 3.2 unique neighbors on land, and approximately 5.2 unique neighbors if we include also maritime borders, then 4 seems to be a reasonable amount of bordering players. Not to mention that the square cell is very easy to formalize. In order to create exactly the same conditions for all players, symmetrical lattice is a necessity and the number of cells in rows/columns is a compromise between what is required by pool of strategies, what is manageable as regards computation time, and what it 'lovely'. Fourteen cells in a row/column make simulation already too slow, while 8 cells do not enable us to use all behavioral rules. 10x10 playing grid is the loveliest solution resembling a kind of Schellingean *focal point*.

4.5.3. Interactions and Payoff Shift

In complex systems modeling there is a shortage of probabilistic nature of interaction occurrence and the proposed model is therefore even more important. It has been already stated that unlike in Axelrod's tournament, in the present model actors do not play against their twins unless there is a difference between number of players and number of available strategies causing subsequently multiple entries of particular decision rule. Since the Prisoner's Dilemma game will be played repeatedly, occurrence of interactions among any given two players must be computed *de novo* every round with updated power factor (spatial position of actors remains stable). Whether two actors will or won't interact in a specific round depends upon the average of two variables: proximity and power. Both of them are normalized to the interval from 0 to 1. In case when their average equals to 1, interaction occurs with certainty, and if it equals to zero, then interaction cannot occur at all. Spatial position variable gets value 1 if the players are immediate neighbors, and it moves towards 0 as their separation achieves the greatest possible value (5 units horizontally as well as vertically on a 10x10 grid). With respect to power variable, it is an average of individual power coefficients computed for each player according to its own position within the system. In general, the greater is the sum of actor's gains compared to average capability level in the system, the closer is the actor's power coefficient to 1. Powerful players thus interact with each other more often than others. Finally, the average of power and distance variables forms the interaction occurrence probability (p) and if this is higher than the number randomly generated from interval between 0 and 1, then interaction occurs. Different numbers of 4950 existing pairs are activated in each round and individual probabilities of interaction occurrence for any of the existing dyads are independent and nonexclusive both with respect to each other as well as between iterations of the game.

Now let me explain these two variables more closely. Model formalizes power as a sum of gains attained from binary interactions. It omits internal sources of power (population, natural resources, extent of territory etc.) in order to remain as simple as possible. To include them would necessitate also formalization of wide variety of phenomena such as mobilizing factor of nationalism, or conquering wars. In this model all players start at the beginning from the same line (equal power) and differentiate only as the simulation proceeds. It is however not sufficient to say that the most powerful states in terms of accumulated capabilities always interact with all other actors in the system. First of all, because of binary interactions we have to compute power coefficients for both players and then make their average that represents overall power variable influencing given pair's interaction occurrence probability. Second, we have to make a difference between various distributions of capabilities within the system.

Imagine two environments with eleven actors each. In both of them ten players have capability levels equal to 10 power units. Yet the last, most powerful state has strength of 11 or alternatively 20 power capability units. These are two very different situations. In the first case, capability level of the most powerful player is very similar to the average level within the system. One cannot say that about the second alternative. To assume the same interaction occurrence consequences for the most powerful players in both distributions would be a mistake because their relative positions differ enormously. Trying to solve this problem, I expect the individual power coefficient (c_i) to be 0.5 in case when state's capability level (W_i) equals to the average level within the system (W_{Avg}). This coefficient is then computed according to the following formulas:

$$\text{(7)} \qquad \begin{aligned} &\text{a.)} \quad \text{If } W_i \geq W_{Avg}: \qquad c_i = 1 - 0{,}5 \text{ x } \frac{\mathrm{W}_{\mathrm{Avg}}}{\mathrm{W}_{\mathrm{i}}} \\ &\text{b.)} \quad \text{If } W_i < W_{Avg}: \qquad c_i = 0{,}5 \text{ x } \frac{\mathrm{W}_{\mathrm{i}}}{\mathrm{W}_{\mathrm{Avg}}} \end{aligned}$$

Apparently, the bigger is the difference between player's capability level and the average sum of capabilities per state in the system, the closer is the individual power coefficient to one of its extremities (0 or 1). Then if we want to determine overall power variable (c_{ik}) that is necessary for computation of interaction occurrence probability itself, we just need to make an average of two examined states' individual power coefficients (c_i and c_k). Proposed way of computing the power variable emphasizes the relational character of power too. This is because we take account of *average* level of capabilities in the system and thus changing power position of some third actor will at the end affect interactions probability of any two examined players.

Resolving the question how to formalize spatial position variable appears at the first sight easier since contrary to capability levels, mutual distance of two potentially interacting players is the same for both of them. Thus one does not have to make any averages. To understand my argument, imagine a square lattice, 10 cells wide and 10 cells long. Closed character of the lattice then secures that the greatest possible distance between centers of two interacting cells is 5 units in latitude as well as longitude. If the cell of a given state has coordinates [x, y], where *x* and *y* are integers from 1 to 10, then the most removed cells have coordinates [x ± 5, y ± 5] and their distance is according to the Pythagoras' theorem 5√2. On the other hand, the smallest possible distance, that of immediate neighbors, is one unit either in longitude or latitude. In such a case, spatial variable (s_{ik}) equals to 1, and if the distance is 5√2, then this variable decreases to zero ($s_{ik} = 0$). Any value of distance falling between these two extremities can then be easily normalized to the s_{ik} interval from 0 to 1. In order to compute spatial variable also for other sizes of the playing grid and not only for the 10x10 square lattice, I then propose the following formulas. First, we need to know, what is the maximum distance (d_{max}) between two players in a given table:

(8) $$d_{max} = \sqrt{\lfloor X_{max} / 2 \rfloor^2 + \lfloor Y_{max} / 2 \rfloor^2}$$

Since our playing grid is a square lattice, to get a maximum distance we simply apply the Pythagoras' theorem upon the floors of overall number of rows (X_{max}) and columns (Y_{max}) each divided by two. Division by two and flooring are required because of the closed nature of playing grid. Then with help of the column (Y) and row positions (X) of players *i* and *k* one needs to choose one of the following four alternatives:

(9)

a.) If $|X_i - X_k| \leq X_{max}/2$ and $|Y_i - Y_k| \leq Y_{max}/2$

$$d = \sqrt{(X_i - X_k)^2 + (Y_i - Y_k)^2}$$

b.) If $|X_i - X_k| \leq X_{max}/2$ and $|Y_i - Y_k| > Y_{max}/2$

$$d = \sqrt{(X_i - X_k)^2 + \left(Y_{\max} - |Y_i - Y_k|\right)^2}$$

c.) If $| X_i - X_k | > X_{max} / 2$ and $| Y_i - Y_k | \leq Y_{max} / 2$

$$d = \sqrt{\left(X_{\max} - \left| X_i - X_k \right| \right)^2 + \left(Y_i - Y_k \right)^2}$$

(9)

d.) If $| X_i - X_k | > X_{max} / 2$ and $| Y_i - Y_k | > Y_{max} / 2$

$$d = \sqrt{\left(X_{\max} - \left| X_i - X_k \right| \right)^2 + \left(Y_{\max} - \left| Y_i - Y_k \right| \right)^2}$$

Now it is already clear that computation of spatial variable is nothing similar to a simple process. Equation (9) uses the Pythagoras' theorem to calculate the value of actual distance (d) between any two players. Then it only remains to normalize this distance to the interval from 0 to 1, so that we finaly get the value of spatial variable s_{ik}. That is what the equation (10) does using the maximum (d_{max}) and minimum distance (one).

(10) $$s_{ik} = \left(d_{max} - d \right) / \left(d_{max} - 1 \right)$$

On the following figure below, you can see what values the spatial position variable gets (vertical axis on the right). The black line is the same for every player when paired with other 99 actors (upper horizontal axis) arranged according to distance in the full model simulations. And you can also notice that the further away from the middle value

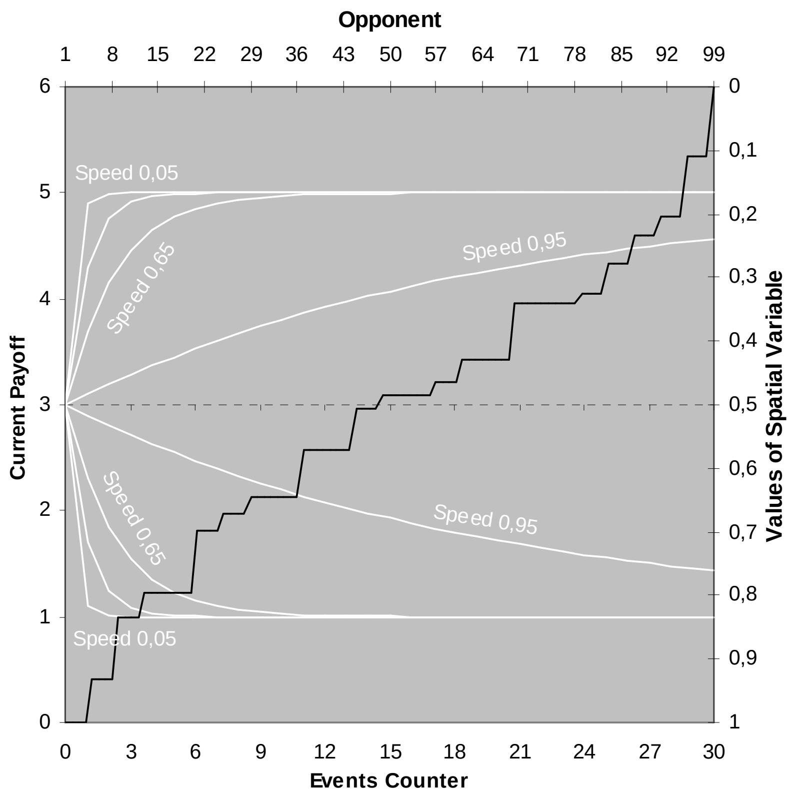

Figure 4: Reward Payoff Change at Various Speeds given Axelrod's Payoffs, and Values of Spatial Variable on 10x10 Lattice.

of 0.5 you look, the steeper is the black line. In other words, there are relatively few very distant as well as immediately neighboring players, but comparatively more opponents with distance equal or close to halfway between two extremities.

In fact, what I did above is only mathematical formalization of the intuitive assumption that the bigger is the distance separating two players, the lower will be the final probability of their interactions. After proposing the formulas for determining values of power (c_{ik}) and spatial variable (s_{ik}), the final step in deciding whether two states interact in particular round of the Prisoner's Dilemma game is to compute interaction occurrence probability and compare it with randomly generated number from interval between 0 and 1. If the overall chance of two actors to interact (p_{ik}) exceeds randomly generated number, their interaction occurs. So if p_{ik} is 0.7, then there is a 70% chance that randomly generated number would be lower than p_{ik} and thus also a 70% chance of two given players' interaction occurrence.

Yet there are several different ways how to compute probability of this interaction occurrence. One can of course determine this probability with help of only one factor, either distance or power. In that case the computation is rather simple and we need only to take the value of the variable concerned and use it as an interaction probability itself. This can serve us very well especially if we want to isolate effects of power and distance upon outcomes of the model. And I did it in my simulations. What interests us the most, however, is the interaction probability based on both of these factors. And here we face three computational options.

First, we can understand two variables formalized above as probabilities of independent events given distance or power of the examined players. Any final interaction occurrence conditioned upon presence of both of them is then a result of joint probability of these two independent events. In other words, $P(A \cap B) = P(A) \times P(B)$. Playing dices and estimating probability of throwing snake eyes can illustrate this situation. This probability is 1/36, which is exactly 1/6 x 1/6 for two independent events, i.e. for throwing two dices. But this way of computing probability of interaction occurrence has a drawback. The theoretical problem is that what we deal with in the real world are not two independent events based on distance and power. We are not computing joint probability of the one interaction determined by distance and occurring simultaneously with other interaction based on power. Even if this were the case, there would be the second, practical problem. Given such computation, there would be no difference between frequency of interactions of two great powers (c_{ik} approaching 1) and two players at the other end of power ladder provided that in both cases actors in these pairs would be maximally distant (s_{ik} equal to 0). There would also be no difference between pairs of two neighboring and two maximally distant players provided that actors would be among the weakest in the system (c_{ik} approaching 0). In all these cases no interaction would occur. This does not make much sense, since states interact when they share border, even if they are not powerful. Great powers frequently come across each other, even if they are from other ends of the world (think about Singapore during the WWII), and the USA interacts with China certainly more often than Guatemala with Bhutan. This kind of interaction probability computation would make appropriate differentiation between these cases impossible.

Second, we can understand the final interaction probability as the union of two events so that instead of requiring their simultaneous occurrence, it would be enough if either of them is present. Given the fact that two events are under this logic non-exclusive since great powers (c_{ik} = 1) can be also neighbors (s_{ik} = 1), then such an understanding leads to the following final probability computation: $P(A \cup B) = P(A) + P(B) - P(A \cap B)$. To illustrate the argument, this computation represents the probability of throwing six OR five on either of the two dices. But besides the theoretical problem common with the previous alternative of probability computation, there is also similar practical problem. In this case, there would be no difference between interaction frequencies of pairs composed of neighboring great powers (c_{ik} = 1 and s_{ik} = 1), or of the most powerful yet maximally distant actors (c_{ik} = 1 and s_{ik} = 0), or alternatively of the least powerful and at the same time neighboring states (c_{ik} = 0 and s_{ik} = 1). Interactions would occur every single round in all these situations. However, this is not how international politics works. Relations between France and Germany were during the end of the 19th century more intense than those between France and Japan (and this similarly holds even now). Not to speak about the frequency of interactions between China and Russia on the one hand, and Kyrgyzstan with Tajikistan on the other. They are anything but similarly intense.

It is the third option of interaction occurrence probability computation that I opted for. In my model I set the value of this probability to be equal to the average of two above mentioned factors of power and distance, because it is the only way how to properly formalize the functioning of the international relations system. Only under this out of the three mentioned computations it is possible to say that no other pair except for the one with two least powerful and simultaneously most distant players (c_{ik} = 0 and s_{ik}

= 0) has the smallest interaction probability in the system. And that the neighboring great powers (c_{ik} = 1 and s_{ik} = 1) interact in every single round unlike states in any other conceivable pair. To get a better picture of my argument, think of cube placed at the origin of three-dimensional Cartesian space where horizontal and receding axes represent distance and power while vertical axis stands for interaction probability. Then if we sum distance and power vectors, project the result via perpendicular upon cube's face diagonal within the distance-power plane, and repeat the same with respect to space diagonal that goes through the origin, then the value of the interaction probability as projected on the vertical axis from the space diagonal with help of yet another perpendicular will be exactly one half of the sum of distance and power variable values.

This kind of probability computation can cope with all practical problems present under the previous computational alternatives, and their solutions perfectly correspond to reality. Even the common theoretical drawback of two alternative computations exists no more, since we are not using probabilities of some independent events to get final joint probability or the probability of some union of events. Instead, one simply takes two different variables and determines how they influence single interaction probability. All this in order to formalize intuitive assumption that the closer two players are and also the more powerful they are, the more often they also interact.

One more factor still remains unformalized. It is the payoff shift. In order to secure comparability of results with the original tournament, reward for mutual cooperation (R) has to comply with the Prisoner's Dilemma payoffs ordering even after the shift. It can therefore move according to pattern of interaction within the interval from T to P, and if additional Prisoner's Dilemma condition of once repeated reward being higher than the sum of temptation and sucker payoffs applies too, then mutual cooperation gain must be even greater than (T + S) / 2. With respect to Axelrod's payoff matrix (T = 5; R = 3; P = 1; S = 0) used also in this model, it means that R can shift between 5 and 1 or alternatively between 5 and 2.5 depending on how strictly we comply with the Prisoner's Dilemma conditions. I will describe how to formalize payoff shift given less strict conditions for payoff matrix, but in the later simulations I of course examine both alternatives. Following equations can be at the same time easily modified to represent the stricter requirements as well.

In order not to overshoot definitional conditions of the Prisoner's Dilemma ordering of payoffs, round by round reward change of the same type will gradually diminish towards the extremities (5 and 1 on the left vertical axis on Figure 4), and it will be more rapid in case when the current reward is close to its initial value from the beginning of the game. Shape of the corresponding reward shift curve depicted as white lines on Figure 4 would, therefore, be that of an exponential function approaching temptation payoff limit in case of continuous mutual cooperation (CC), and of a function approaching punishment payoff limit in case of repeated defection (DC, CD, or DD). Now first, a simple shift counter *r*, whose absolute value is depicted at the bottom horizontal axis, is raised by one every time mutual cooperation occurs and again decreased in case of any defection. It equals to 0 if exactly one half of all outcomes of previous interactions of a given pair is mutually cooperative. Given particular shift speed (*t*) set by researcher at the beginning of the simulation, and as far as what we deal with is a *reward* shift (i.e. shift of the payoff for a CC outcome), then following equations portray how much does overall capability level (*W*) grows after any additional mutually cooperative outcome:

(11)

a.) If $r < 0$ then: $$W_{new} = W_{old} + \left(\mathrm{R} - \left(\mathrm{R} - \mathrm{P} \right) \times \left(1 - t^{|r|} \right) \right)$$

b.) else: $$W_{new} = W_{old} + \left(\mathrm{R} + \left(\mathrm{T} - \mathrm{R} \right) \times \left(1 - t^{r} \right) \right)$$

Current gain from mutual cooperation is a sum of initial reward payoff and corresponding increment or decrement according to history of previous interactions. Swift change of the reward payoff suggests that making a friend or enemy takes a blink of an eye. It can be an example of a system with perfectly informed players that know exactly who they interact with and what kind of behvior they can expect from other players. Just a few interactions suffice for a player in such a system to get to know the other actor in their binary encounters. If we understand payoff shift as a metaphor for the emergence of culture of amity/enmity and thus of (dis)trust, then in such a system trust is created very quickly. Different speeds leading to only slowly changing payoff for mutual cooperation, on the other hand, might be characteristic of systems where the probability of stable pattern of two players’ interactions is rather bleak. In this kind of environment very cautious players look into the future with concern and usually behave according to ‘slow and steady wins the race’ principle with respect to any trust building enterprise. If they do make friends at all, they choose them very carefully requiring relatively long history of mutually cooperative outcomes for reward payoff to aproach temptation (T) in any meaningful way.

Since t belongs to interval from 0 to 1, where 0 represents immediate shift and 1 stands for the exact opposit, then ($1 - t^{|r|}$) can also reach values only from 0 to 1. Given constant t, the first of these two extremes (0) depicts infinitely repeated stable pattern of either mutually cooperative, or defective interactions. It is exemplified by the reward payoff identical to T or P, respectively. The second extreme (1) on the other hand pictures a situation of equal number of mutual cooperations and defective interactions thus causing the reward payoff to stay at the original level set at the beginning.

4.5.4. Strategies

As a way of maximizing robustness of results, application haphazardly distribute players with selected strategies on a playing grid before starting the simulation itself. Repeated simulations thus do not have to start from the same circumstances. Out of total number of 80 available rules, whose written description can be found at the end of the thesis, only 70 actually made their way into the full model. I removed QUAYLE from the original set of 63 strategies used in Axelrod's second tournament, because it was identical to another rule called DOWNING. Moreover, I added another 5 strategies that proved successful in other models and were therefore expected to compete for overall victory. Some of them were interesting improvements of previous versions, while others were completely new. These additions included: WSLS, STFT, GTFT, CTFT, and REMORSE (the last one is described in Boerlijst – Nowak – Sigmund, 1997). Furthermore, I proposed three strategies on my own. All of them ought to mirror the behavior of states in the international relations system. Inspired by work of Stephen Walt on balance of threat theory I dubbed the first one of them WALT. The other two then portray alternative behavior of bandwagoning and balancing the power.

Two comments, nevertheless, have to be stated on account of original set of behavioral rules that I translated from Axelrod's source code. First of all, group of 63 strategies in the second tournament were biased towards cooperative behavior. Majority of rules were nice (40 out of 63), i.e. they never defected first, and overwhelming majority of strategies (56 out of 63) started with cooperation in the first round. Fact that the best unfriendly rule ended up eighth must be approached with this kept in mind. With respect to other characteristics of the rules it is still better to wait until the analysis of results in the next chapter. And second point is that there were some serious bugs in at least five strategies in the original source code (CHAMPION, HALL, FRIEDLAND, FALK, and ROBERTSON). What to do with these bugs is a serious problem when trying to replicate Axelrod's results. One has basically two options. (Wo)man can either accept them as a natural part of the code and use the program without any modifications, or alternatively (s)he can get rid of them. The first option gives you a chance to achieve exactly the same results as original simulations. The problem is that because of the specific nature of these errors, in order to replicate the results you might not only need the available part of the source code that deals with strategies, but also the rest of it, which is however missing. Detailed replication becomes impossible and repairing of mistakes appears to be at least as justified as retaining them. This second option understands those errors as inaccurately formalized behavioral rules. Then if the goal is the greatest possible variability of population of strategies so that we can make plausible inferences from simulation results upon some real world phenomena, then we should repair the code and remove the bugs in order to formalize these rules properly as they were originally intended.

I decided to include all bugs from those five strategies into the first baseline model in order to maximize the probability of successful replication even though I didn't know how precisely original simulations were conducted. My second baseline model and all subsequent variations of it, however, included debugged strategies. Yet if the rerun of Axelrod's tournament with help of the first baseline model would provide same results as those that were published (Axelrod, 1980b), but the second baseline model would not, it would not prove that TFT's success is an artifact. The only thing it would prove would be the fact that in that particular environment (even if very slightly different from the original) TFT was actually outperformed. More important is whether *nice* strategies would win in heterogeneous environment and what would be other characteristics of theirs. But let me stop for a while and deal with those five strategies that contained above mentioned bugs, since they were never analyzed before.

Danny Champion proposed a generous strategy that gained the second highest number of points just after the victorious TFT (Axelrod, 1980b). In the following part of the original source code M represents iteration count and J stands for opponent's decision from the previous round.

```
IF (M .EQ. 1) K61R = 0
IF (J .EQ. 0) ICOOP = ICOOP + 1
IF (M .LE. 10) RETURN
K61R = J
IF (M .LE. 25) RETURN
K61R = 0
```

```
      COPRAT = FLOAT(ICOOP) / FLOAT(M)
      IF (J .EQ. 1 .AND. COPRAT .LT. .6 .AND. R .GT. COPRAT)
    1 K61R = 1
      RETURN
```

If the other player cooperated in the last round, variable that counts overall number of cooperative moves (ICOOP) is raised by one. The first problem is that the ratio of cooperative moves to number of rounds can never be zero, even if the opponent defected all the time. This is because variable that stores the value of opponent's last move is for all players set to be 0 (cooperation) at the beginning of each game. ICOOP is thus raised by one even in the very first round. Properly counted, ICOOP should have been raised only from the second round on. But the impact of this kind of mistake diminishes with the rising number of rounds. The other problem is more serious.

Unlike in case of other strategies, ICOOP variable is not reset at the beginning of each game. This creates a possibility of adding up cooperative moves of different opponents and different games depending on the way how simulation was conducted. Since we don't know the whole source code, we cannot be sure about the effect of this error. There is some small chance that every single game of every single pair of possible strategies was run individually and thus no distortion of COPRAT variable occurred. It would, however, require at least 10080 runs of the program and if we accepted Axelrod's incorrect number of unique pairs (3969), then there must have been even more than 19 800 independent runs. Such a number seems fit for a superhero not a human. On the other hand, if we assume single run and allow CHAMPION to add up cooperative moves across opponents and games as the code suggests, then only after few games with some cooperative opponents ICOOP grows to such an extent that would render defection caused by COPRAT level virtually impossible. Strategy proposed by Danny Champion is thus a fine example of how different possible ways of conducting simulations can influence the magnitude of effects caused by bugs in the program.

Rule designed by James Hall ended up on the 60th place out of 63 competitors. IB and IA variables in the sample below count numbers of defective and cooperative moves, respectively. They are reset to 0 after every even occurrence of a given event and they are set to 0 at the beginning of every game as well. K71R, similarly as K61R in

```
      IF (J .EQ. 0) GOTO 1000
      IB = IB + 1
      IF (IB .EQ. 2) GOTO 500
      K71R = 0
  500 K71R = 1
```

```
     IB = 0
     GOTO 1710
1000 IA = IA + 1
     IF (IA .EQ. 2) GOTO 110
     K71R = 0
     GOTO 1710
 110 K71R = 1
     IA = 0
     GOTO 1710
```

the previous strategy, represents return variable that causes defection if equal to 1 and cooperation otherwise. Line 1710 (not displayed here) is the end-statement. If we consider that both parts of the code, before and after the line 1000, should have a similar structure, it seems obvious that something is missing just before the line 500, namely a `GOTO 1710` statement. If left unaltered, the missing line makes IB variable redundant. After any defection of the opponent (i.e. when J = 1), IB would be first raised by 1, but immediately afterwards reset to 0 again. It would never reach the value of 2. The same effect applies also for K71R and causes HALL to always defect after other player's defection instead of doing that only every other time. This strategy thus exemplifies a situation, when there is no chance to eliminate the impact of a bug by simple manipulation of the way how simulations are conducted.

The third of the five strategies I would like to deal with was proposed by Edward Friedland and it finished 61st, i.e. one place behind HALL and one place before random strategy. Following samples represent two problematic parts of FRIEDLAND.

```
   IF (J .EQ. JL) JSM = JSM + 1
   IF (JSM .GE. 3) JS4 = 1
   IF (JSM .GE. 11) JS11 = 1
   IF (J .NE. JL) JSW = JSW + 1
   JSM = 1
   …
15 POLC = 6 * ALPHA - 8 * BETA - 2
   POLALT = 4 * ALPHA - 5 * BETA - 1
   IF (POLC .EQ. 0) GOTO 40
   IF (POLALT .GE. 0) GOTO 70
   GOTO 60
40 IF (POLC .GE. POLALT) GOTO 50
50 K74R = 0
   RETURN
60 K74R = 1
   RETURN
70 K74R = 1 - K74R
   RETURN
```

It is JL variable that draws our attention. Despite being initialized at the beginning of the simulation, it would never change its value in the rest of the program. The fifth line is even more puzzling. JSM, JS4, JS11, and JSW are variables that can be changed only at the part of the code reproduced here. The fifth line, however, constantly resets JSM to its initial value thus preventing this variable from ever getting above 2. Neither JS4, nor JS11 can then get the value of 1. All four variables appear completely redundant.

```
   IF (J .NE. JL) GOTO 10
   JSM = JSM + 1
   IF (JSM .GE. 3) JS4 = 1
   IF (JSM .GE. 11) JS11 = 1
   GOTO 20
10 JSW = JSW + 1
   JSM = 1
20 JL = J
```

At the same time, necessary correction is very simple. It suffices to make one JL logical conditional statement out of two and to add a single line number 20 (see above) that turns JL from a constant into a variable storing the penultimate choice of the opponent.

Problems of FRIEDLAND strategy, however, do not end here. Execution of logical conditional statement in line 40 of the reproduced original source code has the same result irrespective of POLC and POLALT variable values. K71R always remains equal to 0. Furthermore, if POLC equals to 0 (see the condition two lines below 15), then line 40 can be true only if BETA is lower than or equal to -1, which seems rather impossible given the fact that BETA gets a probability value from the interval (0, 1). Since POLC is actually the difference between expected utilities of always cooperating and always defecting options, and POLALT corresponds to the difference between utilities of persistent defection and alternation of cooperative moves with defective ones, then two small changes of the source code are capable of bringing back the order into chaos (similarity with NEWMAN and DOWNING rules can help us greatly too).

```
   IF (POLC .GE. 0) GOTO 40
   IF (POLALT .GE. 0) GOTO 70
   GOTO 60
40 IF (POLC .GE. POLALT) GOTO 50
   GOTO 70
50 K74R = 0
   RETURN
60 K74R = 1
   RETURN
70 K74R = 1 - K74R
   RETURN
```

First, a new line has to be added before statement number 50. This prevents line 40 from being redundant. And second, equality sign in the opening line needs to be changed to ‘greater or equal’. Fixed code now encompasses all possible expected utility relations between three alternatives of cooperation, defection, and alternation of the former two.

The fourth examined rule written by Roger Falk and James Langsted finished 33rd. Although being a quite complicated strategy, it has relatively simple bug that can be easily identified and corrected. The following sample shows the core of the problem. Since all variables in the sample are of type real, it seems that a digit on the eighth place is scrapped at every iteration, then the remainder is multiplied by 10, and finally 5 is added, so that the result would be again an eight digits long number.

```
100 J5 = J0 / 1E07
    J3 = INT(J5)
    J8 = J5 - J3
    J8 = J8 * 1E07
    F5 = F0 / 1E07
    F3 = INT(F5)
    F8 = F5 - F3
    F8 = F8 * 1E07
    J0 = J8 * 10 + 5
    F0 = F8 * 10 + 5
    …
    IF (J0 .EQ. 11111111) GOTO 920
```

The problem is that both J0 as well as F0 would never change, because even if they are initially set to 0, their value would stay at being equal to 55 555 555 after 8th round. That doesn’t make much sense if both J0 and F0 are supposed to be key variables deciding whether to cooperate or defect. Simple shift from adding 5 to adding J and K85R secures proper functioning of FALK strategy. Scrapping the eighth digit, pushing the previous history forward through multiplication by 10, and updating the history via addition of previous round decisions turn J0 and F0 into effective devices for remembering the last eight iteration outcomes. Unlike the previous bugs in other strategies, FALK contained an error that resembles ordinary typo. No line was missing, no variable was redundant.

The last suspicious strategy I would like to mention is that proposed by William Robertson, which ended up 58th in Axelrod’s second tournament.

```
    IF (M .GT. 1) GOTO 5
    OPDEF = 0
    STDEF = 0
    DL = .20
```

```
    COOPS = 0
    OKDEF = .TRUE.
    MYDEF = .FALSE.
    …
    IF (MYDEF) OKDEF = .FALSE.
    …
 25 K54R = 1
    MYDEF = .FALSE.
```

Part of the code above portrays the lines where the bug distorts proper execution of ROBERTSON. In this strategy, MYDEF and OKDEF represent two binary logical variables. Yet strangely enough, value of MYDEF is never changed to true, which means that OKDEF would also never become false, since it is supposed to change only at the place reproduced above. Sadly enough, OKDEF has a key role in preventing player to initiate defections, if the opponent defected at the same round. Again, the solution of this problem is much less complicated than the strategy itself. MYDEF should shift its value to *true* when player initiates defection. In the following iteration, MYDEF is evaluated and immediately reset back in order to prevent OKDEF from becoming *false* at any other moment except for just after defection initiated by the first player. Stated simply, MYDEF variable has to shift to *true* in the last reproduced statement of ROBERTSON instead of remaining *false*. This error, the simplest one of all considered, nicely shows that even minor and almost imperceptible bugs can cause severe distortion of computer simulation results.

4.5.5. Three International Relations Strategies

I dealt with those of the Axelrod's second tournament strategies that contained serious bugs and could have influenced the whole process of replicating his results. I also enumerated another five rules devised by others that I added to the pool of strategies used in my simulations. Yet I haven't described the balance of threat rule that I proposed based on Walt's work (1994) and included into my simulations as well. Similarly I didn't deal with balancing and bandwagoning as two alternative foreign policy strategies common in international relations.

For many (realist) scholars, balance of power or its later alternative called balance of threat should be a natural tendency within the system. It might be therefore surprising that I haven't mentioned that so far even if I am supposed to model the international relations *system*. I believe that balancing (or bandwagoning) against power or threats is not truly speaking a systemic phenomenon, but rather an individual behavior at the level of units. If this is what the systemic forces allegedly prefer, then such a behavior strategy should prove to be successful in a model that tries to mirror functioning of the international relations system. That is exactly why I reached for Walt's theory and tried to include balance of threat into the pool of strategies. It seems not only superior to balance of power concept, but it also attempts to determine when states opt for bandwagoning instead of balancing (see e.g. Walt, 1994: 29-30). Opportunity to examine the strength of this theory under the circumstances resembling those of the real world international relations system was too tempting to be missed.

Nevertheless, to make a better sense of this strategy, one first needs to identify cooperation with bandwagoning and defection with balancing. This may seem to be a bit overstretched generalization, but if one accepts that continuous mutual cooperation creates trust among players, and also that this (often institutionalized) trust is one of the key characteristics of alliances, then the link between cooperation and bandwagoning seems much less perplexing. The same holds for balancing. Seeing the opponent as a threat or enemy is distinctive feature of balancing and this enmity is precisely the consequence of defective pattern of interactions as already explained in the previous chapter. Moreover, this general understanding of balancing and bandwagoning is not only consistent with the way how Walt used these terms in his writings, it also enables us to better formalize two strategies that balance/bandwagon with respect to power only.

Walt's balance of threat theory includes four key factors that determine what is and what is not a threat. I would like to propose a strategy that would examine (almost) all of them before deciding whether to cooperate or defect.

> Although the distribution of power is an extremely important factor, the level of threat is also affected by geographic proximity, offensive capabilities, and perceived intentions. (Walt, 1994: 5)

Of course the first considered factor should be the power position, but not only because balance of threat is supposed to be a better alternative to balance of power theory. Power is important also because of its key role for determining when balancing and bandwagoning occurs. "[W]eak states can be expected to balance when threatened by states with roughly equal capabilities but they will be tempted to bandwagon when threatened by a great power." (Walt, 1994: 30) Very similar logic holds also for geographical proximity and aggressive intentions. If the opponent is relatively close to the country concerned, the threat it can pose is comparably greater, and thus the probability of balancing behavior rises, "because the ability to project power declines with distance” (Walt, 1994: 23). Likewise, if the state is seen as aggressive, there is little reason to expect bandwagoning from its interacting partners.

> The strong relationship between offensive intentions and balancing behavior is to be expected. … [i]t makes little sense to ally with a state that is known to be hostile, regardless of its other traits. As a result, extremely aggressive states are especially likely to trigger the formation of balancing coalitions. (Walt, 1994: 171; see also 25)

The only difficulty with respect to my model seems to be what Walt has called ‘offensive power’. Aggressive intentions can be easily formalized in the proposed model as a history of interactions while power position and geographical proximity are basically the factors influencing occurrence of interactions. Only the offensive power that Walt distinguished from aggregate power and subsequently defined as “the ability to threaten the sovereignty or territorial integrity of another state at an acceptable cost” (1994: 24) is hard to formalize. I find it as a rather confusing and not sufficiently justified variable. Its explanatory power overlaps with that of power position and aggressive intentions variable, and may possibly be even fully replaced by them. Since I did not want to add another variable into my model just because of this particular strategy, I disregarded offensive power factor of Walt’s balance of threat theory during formalization of its functioning.

Figure 5 portrays the principles that WALT strategy honors while making its choices given particular probability of interaction with any other player and the history of their previous encounters. There is a consistent shift from balancing (defection) to bandwagoning (cooperative behavior) as one moves from the right to the left and from the top to the bottom of that table. As one can see this also corresponds to increase of

<table>
<tr><th></th><th></th><th colspan="4">Share of Mutual Cooperation</th></tr>
<tr><th></th><th></th><th>100-76%</th><th>75-51%</th><th>50-26%</th><th>25-0%</th></tr>
<tr><td rowspan="3">Probability of Interactions</td><td>100-67%</td><td>Almost ALLC</td><td>TFT</td><td colspan="2">Almost ALLD</td></tr>
<tr><td>66-34%</td><td>Almost ALLC</td><td colspan="2">TFT</td><td>Almost ALLD</td></tr>
<tr><td>33-0%</td><td colspan="2">Almost ALLC</td><td>TFT</td><td>Almost ALLD</td></tr>
</table>

Figure 5: Formalization of the Balance of Threat Strategy by Stephen Walt

threat perception as defined by Walt. The history of previous interactions that serves as a proxy for aggressive intentions demonstrates decreasing amount of mutual cooperation as one moves from the left to the right side of the table. Similarly, shift from the top to the bottom of the table corresponds to decrease in probability of interaction occurrence (a kind of proxy for shadow of the future), and therefore to rising distance of the players and/or their diminishing power. Distance and capability level are besides aggressive intentions the other two variables that determine threats according to Walt. Stated plainly, as the threat grows, so does the balancing, i.e. defective, behavior. Situation with the smallest threat perception is the lower left corner of the table, where probability of interactions is low and the previous history demonstrates mutual cooperation. On the other hand, the greatest threat can be localized at the upper right corner, where the previous interactions show little signs of cooperation but at the same time actors interact very often because they are neighbors and/or very powerful states.

The rest is simple. The greater is the threat, the less there is cooperation. Thus after the initial cooperative choice in the first round, one then moves from virtually unconditional cooperation to almost unconditional defection, via TFT strategy that repeats the opponent’s defection but remains prepared to cooperate immediately after the retaliation. Player using WALT strategy first evaluates the probability of interaction with a given player and screens the history of their previous encounters. Only then it makes a choice whether to use defection, TFT, or to offer a cooperative move. Almost always cooperating behavior in this case means that WALT cooperates with a probability equal to the share of mutually cooperative outcomes even after opponent’s defection. Almost always defecting behavior then prescribes that the player defects after other player’s defections and after his/her cooperative moves it cooperates only with a probability equal to the share of mutually cooperative outcomes. WALT thus seems to be very dynamic strategy capable of adapting to unstable environment.

The fact is that balance of threat strategy assumes knowledge of power distribution in the system, which is not always possible to achieve in the real world with sufficient precision. For the modeling purposes it is, however, hardly a decisive point since it is not a matter of being or not being able to perceive the power of others, but only of how accurately one is capable of doing it. There are many far more complicated strategies in the pool and WALT does not use any information unavailable also to other players. It does employ three different decision-making rules, but this is nothing special compared with other strategies in the Axelrod’s second tournament. WALT, and of course the balance of threat theory, moreover displays strong intuitive plausibility, if we consider its application within the realm of international politics. Yet the hopes it raised have to be examined in a contest with other available behavioral rules (but not in the round robin tournaments where any distance variable is absent).

Compared to WALT, the other two strategies that ought to mirror behavior of states in the international relations system are relatively simple. They are focused only upon power and decide to balance or bandwagon respectively as the capabilities of their opponent increase. I named them BALANCE and BANDWAGON just for reasons of simplicity. Both of them pays attention to other player's power variable computed in the same way as already described, when I dealt with interaction occurrence. They also both change their behavior at the moment when this power variable of their adversary exceeds two particular thresholds. Between the values 0.25 and 0.75 they play TFT. Yet as power of the opponent increases BANDWAGON cooperates, while BALANCE defects. Above the 0.75 threshold, the first one of them always cooperates after opponent's cooperation, but it also cooperates even after his/her defection and that with a probability equal to power variable concerned. Below the 0.25 value it defects after defections and after opponent's cooperative move it cooperates only with the probability equal to that power variable. BALANCE behaves in an exactly opposite way. It almost always defects against powerful adversaries (when other player's power variable exceeds the 0.75 threshold) and it almost always cooperates with weak actors (when the parameter gets below the 0.25 value). This is the last of the three foreign policy attitudes I have included in my model in order to find out how they fared.

4.5.6. Data

Having just finished description of how individual features and variables are formalized in my source code, the only thing one needs to add is to clarify what and how much data is required, and how exactly it is going to be processed. I also realize that:

> [s]ound generalizations based on scientific experiments require controlled conditions and sufficient experimental trials in order to distinguish fully their incidental effects from their systematic effects. (Dibble, 2006: 1526)

Therefore as far as it would be possible and manageable, I would try to conduct multiple simulations for each arrangement of initial conditions. Before I introduce complete model with full set of proposed variables, all elementary variations of initial settings would be run for 25 times in isolation. To be precise, after finishing 25 simulations of the second baseline model, I would add spatially dependent interactions feature and run it for 25 times again. The same holds also for power dependent interaction occurrence and payoff shift. As regards the latter, I would consider both conditions for the reward's lower extremity, and also four different shift speeds (0.95; 0.65; 0.35; and 0.05). There is, however, no need to individually examine effects of noise in the second baseline model environment, because many other scholars already done that. Yet the results of simulations that included both power and spatially determined interactions without any noise or payoff shift could be very interesting, and I would therefore do another 25 runs of the program with this specific initial setting that also enables for the first time to introduce WALT strategy.

In order to further strengthen the robustness of results, every single one of all these simulations mentioned above would be run with unique distribution of strategies on a playing grid and for 10 000 iterations each. Of course, this does not hold for Axelrod's design, which used round robin interactions and averaging of 5 tournament's repetitions, each with a different number of iterations. But I would run this first baseline model 25 times with both repaired as well as unrepaired rules anyway. Presented data generating experimental design is clearly intended to isolate impact of individual variables upon the second baseline model and it would hopefully offer the first insight into the functioning of these features. After all, there would be 350 runs of the program with 14 different settings. Then if any recognizable pattern appeared within such a data, I believe there would be no doubts about its validity and robustness

.The last step is the introduction of the full model as proposed and formalized on previous pages. Every initial setting would contain specifications for noise level, as well as speed of payoff shift, and it would also include both factors of interaction occurrence determination. Each setting would be run 100 times and for 10 000 rounds each, with changing initial distribution of strategies, and the same (zero) initial power level. I expect little or no difference between effects of two different lower limits for reward shift. I also expect that the impact of shift speed would be clearly articulated by two extreme cases (0.95 and 0.05 level, or in other words, rigid and immediate shift). If preceding simulation results prove something else, I will be ready to modify intended full model initial settings, but otherwise I would stick to reward payoff shifting within the interval from T to P at the speed of either 0.95 or 0.05, and with the noise level of 1%, 3%, or alternatively 5% that applies both for misperception and misimplementation. Even this restricted plan for simulations, however, necessitates 600 runs of the program.

Just for controlling purposes, I would, furthermore, conduct 25 simulations of the full model with added 3% misperception level, (T + S) / 2 as the lower extremity for reward shift, and 0.35 as the speed of this shift. Similarly, 25 runs would be done under 3% misimplementation level, (T + S) / 2 lower margin, and 0.65 speed of reward shift. All in all, this makes for exactly 1000 runs of the program.[5]

With respect to what data is necessary for answering the research questions, I am interested in three different types of information related to individual players: overall level of achieved gains; number of interactions with any given opponents relative to overall number of iterations; and number of mutually cooperative outcomes with particular player given number of their interactions. Successfulness of behavioral rules would be assessed via overall accumulated gains and the average final rank of the strategies. In case there were more players using some specific rule, the one with higher final capability level would be picked up as regards successfulness evaluation. Number of mutually cooperative moves given overall number of interaction can together with written description of particular strategies provide some clues with respect to what characteristics (generosity, retaliation etc.) are crucial for success in the contest. It can also provide some hints regarding impact of model's individual features upon overall cooperativeness of players. Finally, inclusion of both interaction occurrence variables makes worthwhile introducing frequency of interactions between players as a measure that can say a lot about degree of interconnectedness of the population and clarifies the problem of possible small-world or scale-free network emergence.

Now what to expect? There is no way how to know that simply just by some kind of probability estimate before finishing the simulations and analyzing the data. Yet given the previous models and composition of the present one, there is some place at least for an intuition. I expect that winning strategies would be characterized by a generous behavior; that interactions would lead towards emergence of the small-world network; and of course I also hope that the newly proposed strategy would be very successful. Let's see what would just turn into a wishful thinking, and what would turn out as a correct estimate of the reality.

[5] Several important changes and updates were made during the data analysis. Counterintuitive nature of results from specific settings forced me to double-check and rerun the program with power variable, distance variable, and ultimately both of them coupled with small level of noise (3% of both kinds). I also decided to add the final control setting in which I populated the environment with the new VIENNA strategy. It has unique, randomly chosen probability values of cooperation after each of the four possible outcomes of the game. To this strategy I added the most prosperous rules from the previous simulations in order to examine their success in a completely different pool of players. Thus I did 1100 reruns in total.

5. Results

As I mentioned above, most of the strategies included in my model were translated into the C# language from more than 30-year-old Axelrod's source code written in Fortran 77. To be sure that I did it correctly, I introduced the first baseline model. It represents necessary initial link in a chain connecting Axelrod's second tournament results with those of the full model presented in this thesis. The settings included all 63 original strategies that interacted with each other in the round-robin manner and also with own copy. Each of the 25 reruns of the program that I conducted to achieve robust results consisted of 5 independent tournaments, which similarly as in Axelrod's contest had 63, 77, 151, 156, and 308 iterations respectively. There wasn't any noise, payoff shifts, or any other additional features that were not included also in the Axelrod's design. The Prisoner's Dilemma matrix appeared in exactly the same form as in the original settings, i.e. T = 5, R = 3, P = 1, and S = 0. After five tournaments in every run of the program, payoffs received by individual players were summed up and the winner was determined based on the highest level of total gains. The final rank of all 63 rules was then computed as an average place in those 25 reruns. I have done separate simulations both with repaired as well as unrepaired versions of the five erroneously formalized rules described in the previous chapter. Graphical depiction of the results concerned can be found on the next page.

The most significant outcome of the replication of Axelrod's second tournament settings with help of the source code written in C# instead of Fortran 77 is the fact that TFT strategy won the contest when competing in the pool with both repaired and also unrepaired rules. Under the best possible scenario, rules would be placed on a straight line from the bottom left to the top right corner of the pictures below, where the horizontal axis represents ranking of the given strategy in the Axelrod's tournament and the vertical axis stands for the rank in my rerun of the original settings. Yet many strategies are probabilistic and there are also those bugs that I had already mentioned. Achieving exactly the same results can, therefore, be very difficult, and even more so if we consider the fact of missing source code of the way how the original tournament was exactly conducted. Nevertheless, my results indicate very high degree of correspondence with Axelrod's outcomes.

In case of simulations with unrepaired rules, there is a 0.964 correlation with original ranking of strategies, while repaired list of rules indicate only a slightly lower correlation of r = 0.914. Just four strategies in the former and six in the latter case

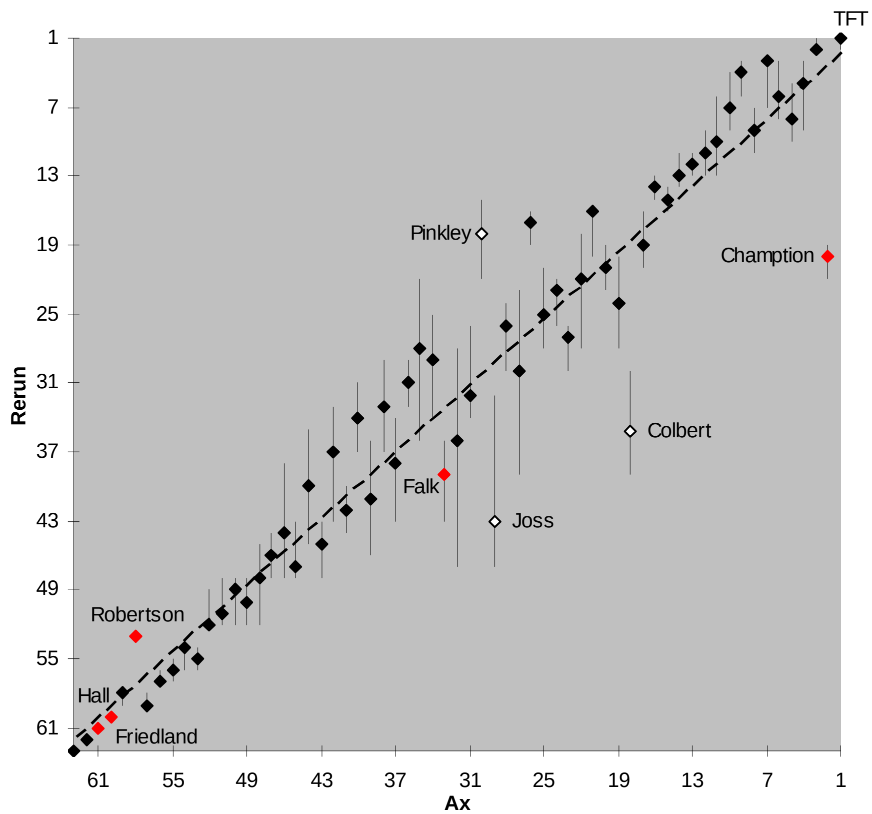

Figure 6: First Baseline Model (Unrepaired Rules)

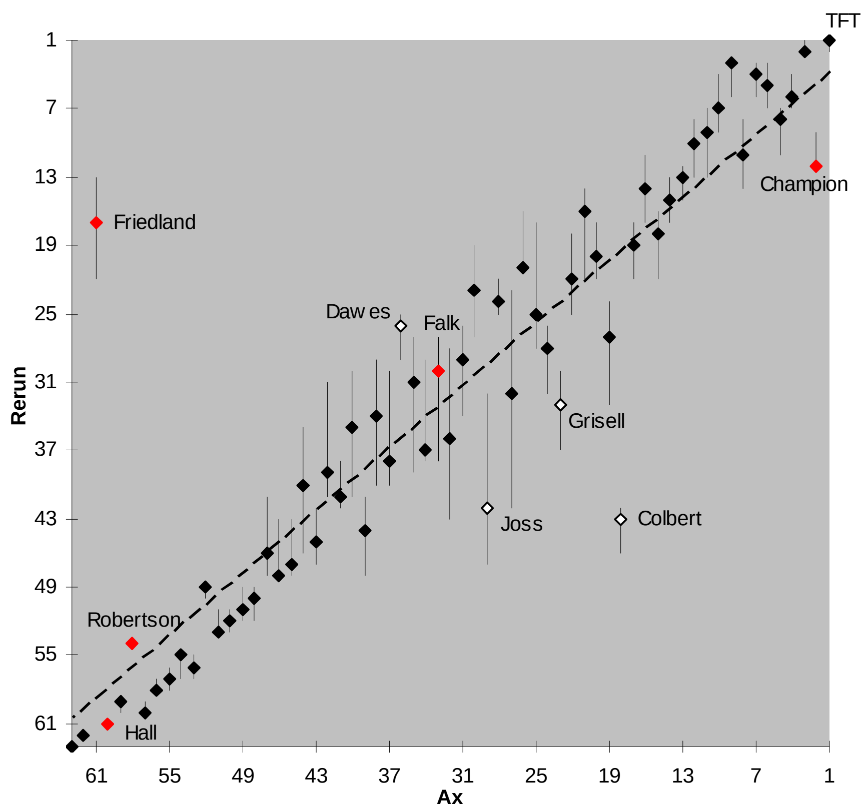

Figure 7: First Baseline Model (Repaired Rules)

shifted from their original positions for at least 10 places keeping thus the average degree of departure from the original standing at the low level of 3 and 4 places respectively. Moreover, one-fourth or alternatively one-third of these large deviators can be explained by those five rules with bugs (colored in red). Particularly interesting is the case of FRIEDLAND rule, which initially ended up only 61st out of 63 contestants, but after removing the bug this strategy significantly improved its performance and finished at the 17th place. Similar but somehow smaller amelioration of acquired gains occurred also to CHAMPION strategy that jumped from 20th to 12th place after having its source code repaired. As regards other rules that departed from their original positions for at least 10 places (colored in white) and were not simultaneously one of those five special cases with bugs, three-fifths of them (PINKLEY, JOSS, and COLBERT) were formalized in the Axelrod's code in not particularly effective way thus suggesting the possibility, even if not the necessity, of still other bugs. Moreover, PINKLEY, which deviated 12 places from the original results within the pool with unrepaired rules, but only 7 places within the one with repaired strategies, was at the same time also one of the five so called *representatives*. These were capable of predicting the success of all other rules in Axelrod's tournament (see 1980b: 386).

Last but not least, one can also notice different variability of the rank achieved by particular strategies in individual reruns of the game (solid vertical lines). As is clear from the figures above, high level of this variability dominated mostly the middle area of the final list of rules sorted according to the overall gains achieved, while lower levels of this variability were symptomatic for rules that finished at the top and at the bottom of the list. Ranking of two rules (PEBLEY within the unrepaired pool and FEATHERS within the repaired one) even varied for almost 20 places. And here again, one of these two rules, namely FEATHERS, is yet another *representative* identified by Axelrod. The puzzling question is, how can a strategy with such a great variability of the final rank under identical conditions be a useful tool for predicting the ranking of other rules in the population? Still another problem is how to interpret the concentration of high level variability in the middle of the list? One is tempted to see this instability in the final ranking as a consequence of probabilistic features within these strategies, but RANDOM, which is a probabilistic rule par excellence, finished consistently at the penultimate place thus exhibiting zero variability. Maybe a better explanation would be a certain kind of threshold partly dependent on some randomly generated number. If reached quickly after launching a simulation, this threshold can cause occasional big shifts in achieved gains of the strategies concerned. Similarly great shifts, but in the opposite direction, occur if this threshold remains unsurpassed for the whole game. One way or the other, my aim here is not to analyze Axelrod's pool of behavioral rules in any detail. The most important thing for me is the high correlation between the original results and those generated with help of repaired strategies. Together with the fact that TFT won the replicated contest and that both the most successful as well as the least successful rules were virtually the same as in the Axelrod's second tournament, it allows us to say that, given the circumstances, one has translated the strategies from Fortran 77 into C# accurately enough. This opens up the way for using repaired pool of rules in all subsequent simulations while simultaneously keeping explicit connection with the Axelrod's original results and with the success of TFT.

After replicating 30-year-old Prisoner's Dilemma tournament outcomes, one can slowly begin to relax some assumptions in order to move towards the full model as proposed in this thesis. The second baseline model is precisely such a step. Its settings was almost the same as in the previous baseline model, but instead of 5 variously long independent tournaments in every rerun, all 25 simulations now included exactly 10 000 rounds. Moreover, players did not interact with own copy and there were also five new strategies introduced, which scholars dealing with multi-agent simulations proposed as promising alternatives to TFT rule. One of these newly proposed rules in fact really got to the top of the list. Generous version of TFT that with a certain probability forgave opponent's defection without punishment won 20 out of 25 second baseline model simulations. The level of generosity was in this case set according to Molander's optimality criterion described in the first chapter above. At the same time, however, there were 3 other strategies that won at least one rerun of the program. Pure TFT did not manage that (it finished second once), but variability of winning strategies was still much higher than in case of the first baseline model results, where only one strategy besides TFT was capable of finishing at the top (BOERUFSEN). Thus at the end it seems that generosity dominates the Prisoner's Dilemma contests even in absence of any noise while outcomes simultaneously underline the competitive advantage of reciprocal rules like TFT or its close modifications.

Several other things seem to be equally important when dealing with the second baseline model results. First of all, there was a very high correlation (r = 0.920) with results of the first baseline model that used repaired set of rules. After simple rescaling

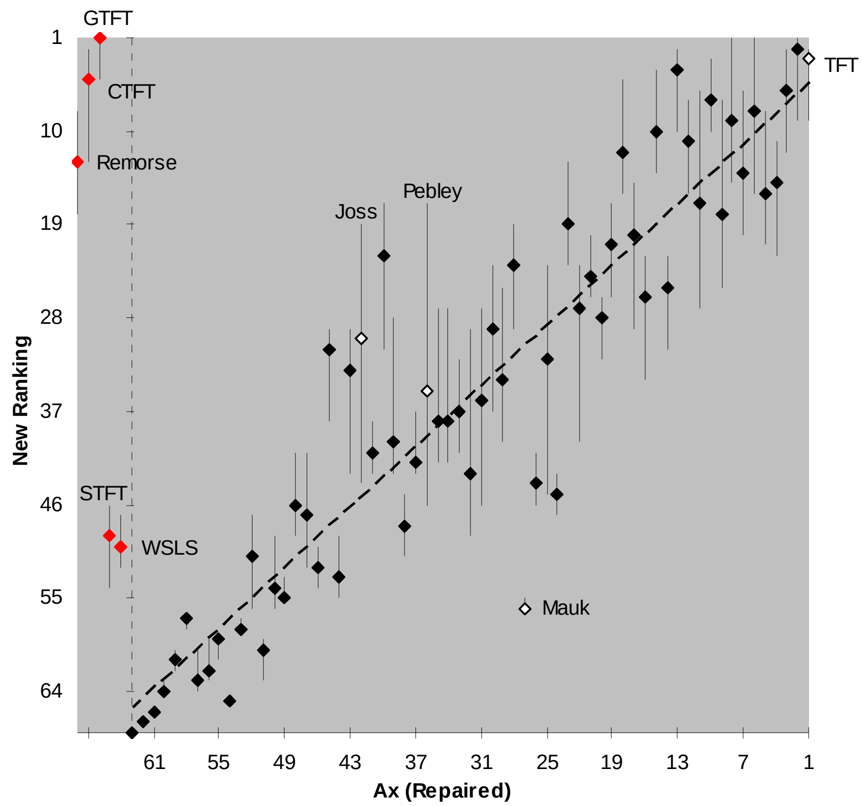

Figure 8: Second Baseline Model

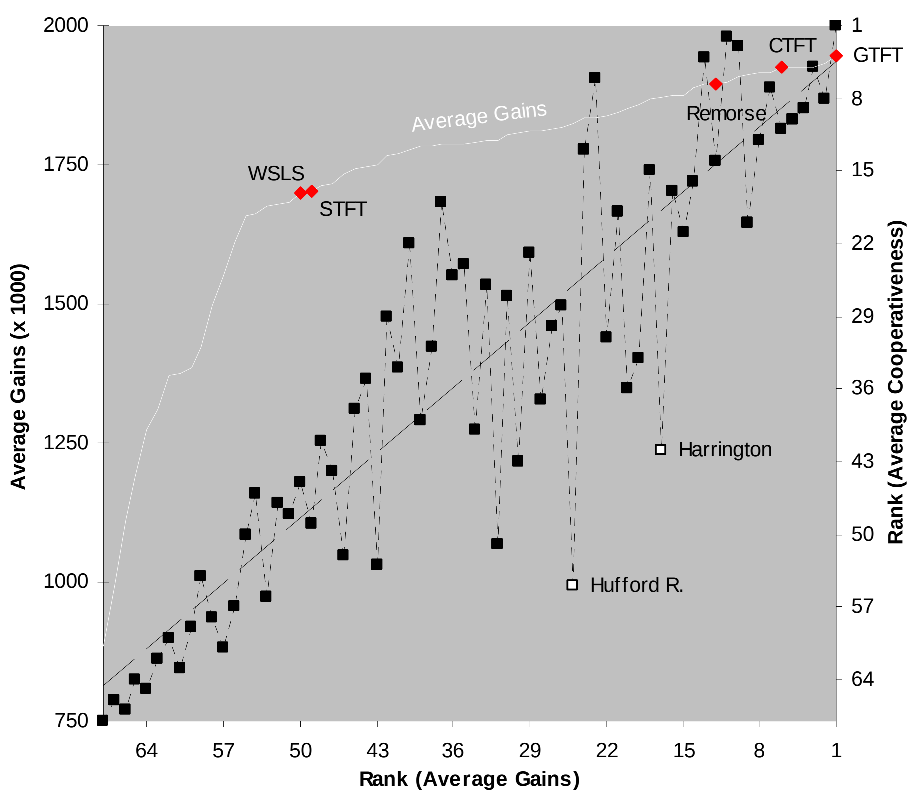

Figure 9: Second Baseline Model (Cooperation Success)

of the ranking of individual strategies from 1 to 68 into the interval from 1 to 63 one thus finds out that a strong level of comparability between Axelrod's and new results is still well preserved. Consequently, an average deviation in the population remained at the low level of 5 places and this holds even though three out of five newly proposed behavioral rules ended up very high. We already know that GTFT was the first according to the average rank achieved. Moreover, CTFT finished fifth and REMORSE received enough payoffs to get to the 13th place. Pavlovian WSLS and suspicious version of TFT, however, fared badly (50th and 49th place respectively). Yet after rescaling only one strategy (MAUK) departed for more than 20 places from the first baseline model position. And the most plausible explanation for that seems to be its tendency for defective behavior after few dozens of interactions with generous players, which provokes punishment only from the long-time perspective. This could clearly not have occurred in the original settings with only three hundreds iterations at most. Finally, two strategies already mentioned above (JOSS and PEBLEY) manifested the greatest variation in their relative success, since their ranking shifted for more than 25 places between individual simulations. This is in fact higher variation than in the first baseline model, but most probably attributable to simple increased number of iterations.

Something different can, nevertheless, tell us more about the character of the whole pool of strategies used in these simulations. As one can see from the white line on Figure 9 above, the first 55 out of 68 rules had extremely small differences between their respective levels of acquired gains (vertical axis on the left). GRIM (the 55th strategy) still gained 85% of the winner's total payoffs, but then overall capabilities declined much faster. The last player managed to get only 45% of payoffs received by the winner. Apparently there must be some bias in such a population, when we get this kind of results. Actually it is the cooperative character of rules described in the previous chapter that caused that. Axelrod stated that the first mean strategy in his tournament ended up eighth and no other appeared among the first 15 rules. In my second baseline model, the best player willing to defect first finished 17th being at the same time the sole representative of this group among the 24 most successful strategies! On the other end of the list, no nice rule appeared after the GRIM. Thus all of the last 13 players were prepared to defect even without being provoked by the opponent's defection. Moreover, out of the last 26 strategies, 19 were mean and only 7 were nice. In other words, almost 80% of non-nice rules were concentrated among the least successful three-eights of the population. Not to speak about the fact that the remaining meanies tried to defect mostly once or twice and then quickly shifted back to cooperation.

Nice illustration of the impact of cooperation bias on success of competing strategies is distribution of black markers (see Figure 9 above) that corresponds to the relationship between ranking according to total gains (lower horizontal axis) and ranking based on average number of mutually cooperative outcomes per opponent (vertical axis on the right side of Figure 9). To make a long story short, the higher is the cooperativeness of a strategy, the greater is also its sum of gains (correlation r = 0.896). Only two rules, HARRINGTON and HUFFORDR, deviated significantly from this tendency. Finishing much higher on the success list than suggested by the number of mutually cooperative outcomes they were able to generate in interactions with their opponents, these two strategies represent the only mean players among the first 29 contestants. It would be quite interesting to see, whether cooperativeness predicts also success in a noisy environment with all features of the full model proposed in this thesis included. That is because under uncertainty even nice players occasionally defect first.

5.1. Impact of Individual Variables

But before proceeding to the examination of the full model results, one first needs to determine the impact of individual variables present in the model itself. Some findings are in fact quite interesting. For example, it seems that none of two structural variables (distribution of power and spatial position) that I included in my model, and which determined the occurrence of interactions, have any significant impact upon success of competing players. On the other hand, the third novelty, that of shifting reward payoff, wields a big influence upon outcomes of simulations. Settings of simulations were at the same time identical to those of the second baseline model with only three exceptions. I excluded QUAYLE strategy from the pool, because it was the exact copy of DOWNING, which was already present. Thus there were 67 unique behavioral rules at the end (62 original plus 5 new). Second, those 25 reruns of the program, in which occurrence of interactions were determined by both distance and power position of the players, contained three additional strategies formalized according to the patterns of behavior common in the international relations system, i.e. balancing, bandwagoning, and Waltian balancing against threats. The pool therefore increased to comprise 70 rules. And third, I raised the number of players in individual simulations to 100. Up until now, this number was equal to the number of unique strategies. In case of the

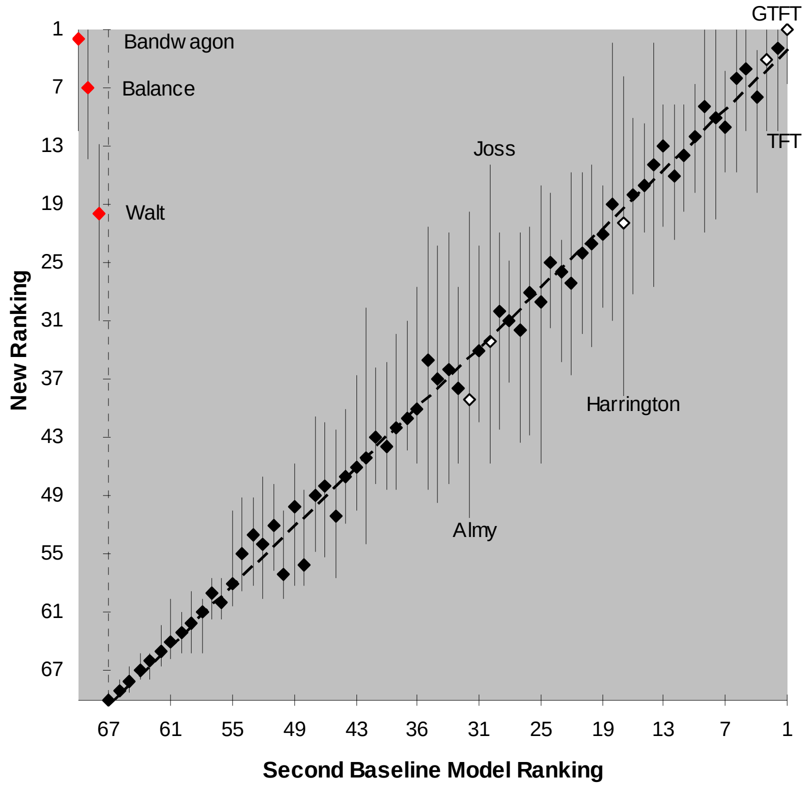

Figure 10: Interactions Based on Both Power and Distance

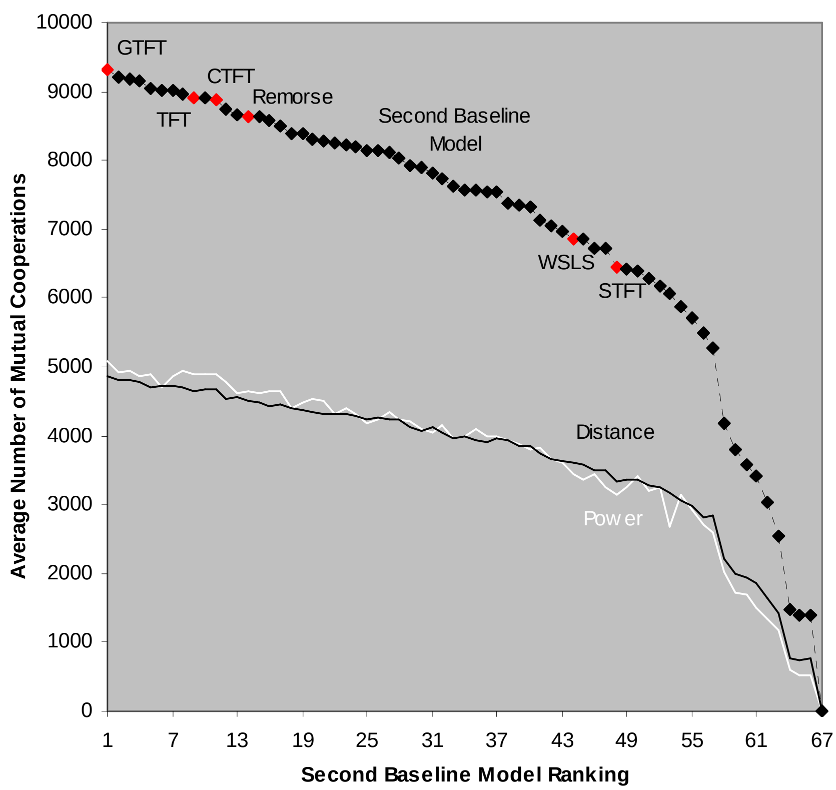

Figure 11: Distribution of Mutually Cooperative Outcomes

Axelrod's tournament, strategies interacted also with one's own copy, yet this copy was not included in the final results since it didn't interact with any other rules. In order to ensure higher heterogeneity and to enable occasional interactions with other actors using the same strategy, I added more players so that their number would be higher than number of available rules. Some strategies would hence appear more than just once.

My expectations were that other than round-robin pattern of interactions occurrence would have some effect upon success of strategies. That for example preference for interactions with more powerful players would lead to the better differentiation among individual rules than achieved in the second baseline model, simply because the most potent players would interact most often with other actors successful in securing high gains. This was, however, not meant to be the case. In a noiseless environment, results of the second baseline model correlated extremely well with the reruns that used power, distance, or even both of these variables to determine occurrence of interactions (r = 0.997; 0.995; 0.996 respectively). Under all of these settings the outcomes were basically identical with those of the baseline model and players were distributed on or closely along the line from the bottom-left to the top-right corner as on the Figure 10. There the y-axis represents average ranking of rules in 25 simulations, in which interactions were determined by both power and distance, while minima and maxima of individual rules' achieved rank are rescaled from the interval between 1 and 100 into the one from 1 to 70.

In fact this identity of results with those from the round-robin second baseline model can be at least partially explained. In a well mixed heterogeneous population randomly dispersed on a playing grid, sufficient number of reruns secure that the distance variable has the same impact upon all strategies. Actors don't change their spatial position except for between individual reruns, and thus there is no feedback loop present in this variable. In a given run of the program players interact in all rounds with the same probability that gradually decreases depending on their distance. Relatively high number of simulations guarantees that no distribution has a preeminent influence. There are therefore only two significant effects of this spatial variable.

First, it significantly limits average number of interactions per opponent. Immediate neighbors achieve uninterrupted interactions for 10 000 rounds, but the most separated actors don't come across each other at all, thus indirectly halving the average number of mutually cooperative outcomes per player per opponent in the population (vertical axis on the left on Figure 11) from almost 7000 in the second baseline model depicted by black markers to little more than 3600 under spatially determined interactions portrayed by the full black line decreasing from left to right on Figure 11. Note also that this line representing average cooperativeness is almost perfectly monotonous. The ranking of strategies based on mutual cooperations in the second baseline model (horizontal axis) is thus kept virtually intact.

And second, occurrence of interactions dependent upon initial distribution of actors on the lattice brings about much higher variability of achieved ranking than we saw in both baseline models. No less than eight rules (including TFT) were able to win at least one out of 25 contests and the average number of places that strategy varied for was almost 26 in the population of 100 actors. Position of two rules (HUFFORDR and GETZLER) even shifted for more than a half of the whole list, which is extremely high variability considering the corresponding number for the second baseline model (1/7 of the list). Yet the effect upon average ranking of individual rules was miniscule, if any.

The impact of power variable is a more difficult story to tell. Here, there is a feedback loop between players' actions and their future interactions, because the most successful actors face each other most often. I therefore expected anything but results perfectly identical to those of the second baseline model. The way of pairing actors was completely different from that of the round-robin arrangement, and as far as the success of strategies/actors depends on opponents they face, there should be little reason for outcomes to be exactly the same. However, distribution of overall gains achieved as well as average number of mutually cooperative outcomes per opponent (see the white line on Figure 11) were at the end basically identical with values achieved using the spatial factor for determining interaction occurrence. And of course the general ranking of strategies matched the one under the second baseline model settings.

The only plausible explanation for that I could come up with is the general cooperative bias of the population. The fact that most players cooperated most of the time led to high population average of the final capability levels (almost 83% of the winning strategy total gains) while at the same time two thirds of actors achieved higher overall payoffs than was the average (basically the same shape of curve as on Figure 9). Given the way how power variable was formalized, this caused that there were generally only small differences between interaction occurrence probabilities of any two players. Even the two most successful rules interacted with each other with probability of just 58% while probability of interaction between the 10th and the 11th least prosperous strategy was only 20% lower. In other words, almost all pairs interacted almost equally often and thus the results must have been the same as in the second baseline model. The only effects of power variable worth mentioning were nearly unrecognizably steeper slope of the gains curve (winners got slightly more and losers got slightly less) and lower variability of rules' ranking compared to spatial variable determination of interaction occurrence. Only five strategies managed to win at least once and rules varied in average for 1/6 of the whole list compared to 1/4 in the previous case.

If nothing else, I hoped that inclusion of noise would at least somehow balance out the impact of prevailing cooperativeness by revealing differences between various ways of coping with uncertainty, and thus strengthening the influence of power variable by increasing the gaps between players' overall gains. But the only thing it did, except for radically reshuffling the ranking of rules, was to make the slope of the gains curve more evenly decreasing and thus mitigating sudden fall in overall payoffs among the least successful players. Note that I am concerned here with the effects of power and distance upon interaction occurrence in a noisy environment rather than with the effects of noise itself. The latter is already well analyzed in the literature and it suffices to deal with it together with examination of the full model. I therefore rerun the second baseline model with small 3% noise of both kinds and compared these new results with outcomes of simulations that employed power and spatiality under uncertainty. While using power variable to determine interaction occurrence, the average sum of gains in the population actually declined a bit compared to noiseless settings, but only to little less than 74% of the winning strategy level. The least successful rule still received more than 40% of the winner's payoffs and ranking of strategies was again basically the same as in the noisy baseline model.

Outcomes of simulations that included both power and distance variables in computation of interaction occurrence are then just a corollary to what was already written above and what holds for both uncertain as well as noiseless environments. While the factor of space enhances the ranking variability of individual strategies, and power very slightly increases the steepness of population's gains curve, inclusion of both factors gives us a compromise of somehow smaller average variability of rules' ranking and even less recognizable increase in the steepness of the curve concerned. Moreover, uncertainty had no effect upon the impact of two examined factors when employed jointly, except for the fact that single rule won all reruns in the noisy environment (it was WHITE, but more on that strategy later). Overall variability of individual rankings under the same settings was similar to the case without any noise and list of average rankings of strategies was basically identical with that of the noisy second baseline model. Thus it seems that two systemic factors usually understood as the most important variables in the international relations system, i.e. power and distance, have very little or no significant impact at all upon success of competing actors. Of course, distribution of power in the real international relations system is a bit different than that at the end of individual simulations, but even if I had run the program for more than 10 000 rounds or enabled uneven initial capability levels at the beginning of the game, I do not think any major changes would have occurred. Most probably, initial differences would have been quickly leveled after few dozens of rounds, and if anything, then the only thing worth of notice would have been modified slope of the curve, but certainly not different final rankings.

Few more things at the Figure 10 may attract our attention as well. All of the three newly added behavioral rules, BANDWAGON, BALANCE, and WALT, were very successful and ended up 2nd, 7th, and 20th respectively, receiving something between 99.5% and 95% of the winner's payoffs. Especially the former two received high payoffs thanks to TFT strategy they employed most of the time during the game. Yet their preclusive success must be, nevertheless, approached cautiously and implications should be drawn only after investigating their performance under full model settings. And similarly for the structure of interactions, let me deal with the impact of both variables inclusion into interaction occurrence determination a bit later after introducing the full model itself. Last but not least, remarkable is also extremely high variability of final rankings of another three strategies (JOSS, HARRINGTON, and ALMY) caused predominantly by distance variable and reaching as high level as 44 places or more out of maximum of 100.

Besides power and distance, there is, however, one other feature newly included into the model and still unexamined so far, namely payoff shift. I already wrote that reward payoff for mutual cooperation can shift in response to outcomes of the previous interactions, and this within two different intervals depending on how strictly we want to observe the Prisoner's Dilemma conditions. One can also set various levels of the payoff shift speed and I did it too. Four different speeds were examined using two intervals, hence giving rise to eight different settings. The slowest pace of payoff shift I considered was 0.95, the fastest one equaled to 0.05, and 0.65 together with 0.35 represented values somewhat in between. Since my intention was to investigate the

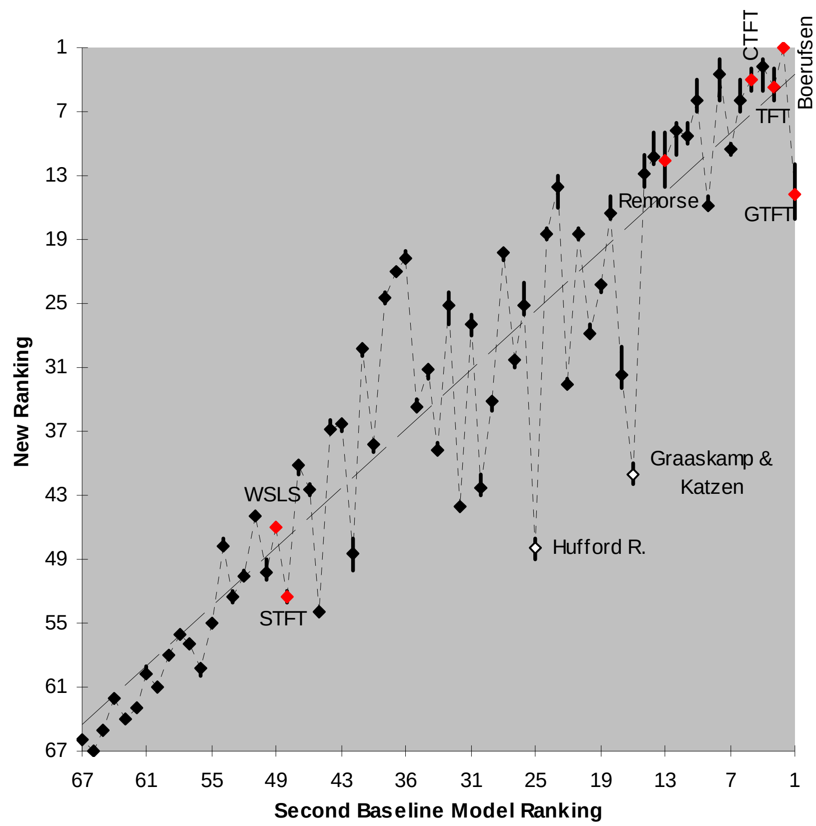

Figure 12: Punishment as the Lower Payoff Shift Limit

impact of payoff shift in isolation from other variables, especially power and distance of actors, 25 reruns were conducted under each setting in the noiseless and most importantly round-robin environment with 67 strategies.

But the results suggest that both of these intervals (from 5 to 2.5, and from 5 to 1) have the same effect upon success of individual strategies. Corresponding outcomes correlate at the very high level (r = 0.996). This basically supports my expectations and justifies the decision to use only one interval, that between temptation and punishment payoffs, in all later simulations. The question of why is that, nevertheless, remains. It seems that from such a long perspective as 10 000 rounds represent, there is no difference between two intervals of payoff shift because mostly cooperative pattern of interactions between any two players gets settled already after few hundred rounds at most. Reward payoff quickly moves towards one of the two ends of the interval and stay there till the end of the game. We will see later when analyzing outcomes of the full model and of the control simulations, whether noise can change anything about that.

Under both intervals of payoff shift four different speeds were examined. Vertical black lines on Figure 12 connect minimal and maximal average ranks any given rule achieved under those four speeds, when reward shifted between temptation and punishment. Black markers these lines go through depict averages of the same four values for any particular strategy. These lines are very short or non-existent. It holds regardless of the lower limit of the reward shift, which means that not only under both intervals, but also under different speeds all rules achieve virtually the same ranking. Relatively small number of iterations suffices to shift the reward payoff to such a degree that subsequent modifications have little impact and differences in overall gains produced up to that moment are too miniscule to be significant at the very end of the game. Yet again, let us wait with the final conclusion until examining noisy environment and stay for now with the statement that it might be enough to pay attention only to the single interval and two speeds, i.e. the highest and the lowest one.

As regards further analysis of the impact of individual variables, it might be also interesting to know that the distribution of power (or gains, if you want) at the end of simulations was much greater than under the previously examined features. Capabilities of the least powerful player were only one-fourth of the winner and all this even without inclusion of uncertainty. Compare this to 45% of the winner's gains as the corresponding number for the second baseline model. On the other hand, more than doubling of the winner's final capability level changed little or nothing with respect to shape of the gains curve in the population. Similarly as in the baseline model, there still remained that sudden drop at the end of the success list. But let me deal a bit more also with some of specific outcomes of payoff shift inclusion into my simulations.

First of all, GTFT ceased to be the most successful rule. It was actually BOERUFSEN that received the highest average ranking under all of the eight settings. This strategy improves the performance of TFT by trying every 25 moves to identify defectors and random players among its opponents and by attempting to prevent the unfolding of echo effect of unilateral cooperation and defection. Another 4 or 6 rules were always able to won at least once under different settings and TFT or its small modifications like GTFT or CTFT managed to do that in most environments as well. It was GTFT again whose four average positions under both intervals differed most. In general, its average ranking decreased as one moved from very slow towards very fast pace of payoff shift. Success of this rule also changes slightly when we fix the speed but alternate two available intervals. It ranked 15th, 15th, 13th, and 8th in average while using (T + S) / 2 as the lower limit for payoff shift and four different speeds in decreasing order of velocity, respectively. Similarly, it occupied 17th, 15th, 15th, and 12th post for corresponding speeds using the alternative interval of the payoff shift. Behind the slightly worse performance in the latter case one can see the influence of the lower end of the interval. The one that equals to 1 instead of 2.5. After repeated defections, the level of reward payoff can simply decrease less while using (T + S) / 2 as a bottom margin for payoff shift, hence causing any recovery towards temptation payoff after resumed mutual cooperation to be more profitable and overall gains higher at the end.

With respect to different positions under different shift speeds, one has to realize that given the computation of GTFT optimal generosity level the possibility of immediate transformation of reward payoff into temptation or punishment in fact hinders any possible effect of limited forgiving without retaliation. Fast payoff shift forces GTFT player to either always cooperate or always defect after opponent's defections depending on the history of previous interactions. On the contrary, slower pace of payoff shift still leaves enough space for limited generosity, especially when current value of reward payoff is still far away from T or the lower end of the interval. This is basically also the reason for weaker performance of generous tit-for-tat after inclusion of amity and enmity into the round-robin second baseline model.

But as one can see, many other strategies changed their positions on the final success list as well. Ranks of two of them, HUFFORDR and GKATZEN, even shifted for 20 or more places. Nonetheless, after rescaling the second baseline model ranking into the interval from 1 to 67, there still remains a clear tendency of individual rules to be arranged along the line from the bottom-left to the upper-right corner of Figure 12 above. Correlation between average new ranking and the one from the second baseline model also remains very high (r = 0.933 for the payoff shift lower margin equal to 2.5 and r = 0.924 for the one set at the high of 1). This is a correlation level similar to that achieved by two versions of the first baseline model when compared to the original results or between the second and the first baseline models themselves. Also the very behavior of one of the five representatives identified by Axelrod (namely FEATHERS), which were together capable of predicting the success of any rule in the population, was significantly influenced by the emergence of enmity and amity out of dyadic interactions. This might be a coincidence but as well an example of the fact that this newly introduced feature has impact not only upon the total sum of accumulated gains, but also upon behavior of individual strategies as such.

Anyway, what one can clearly recognize is that payoff shift has a noticeable impact on the ranking of rules. It only supports the statement that the possibility of friendship and enmity does matter in the international relations system. Coupled with the previous findings it means that instead of spatial position or power, it is the understanding of the opponent as either friend or enemy based on the history of their interactions that codetermines who is successful and who is not. In other words, it seems that it is not the factors at the systemic level, but rather those at the lower sub-systemic one, that make a real difference in the international relations. This doesn't mean that it doesn't matter who is your neighbor; or how powerful is the opponent you interact with. Of course that it can influence how well you are able to perform in the system, or whether you can survive at all. But what it also means is that many things are just a matter of chance and not necessity. It is a matter of chance whether your neighbor cheats on you, or instead prefers cooperation, similarly as it is just a matter of chance whether your partner is a superpower or a petty city state. The key is to distinguish particularities and to focus rather on what occurs in the system all the time. Or at least most of the time. If we want to know how the system works, we need to take a bigger picture, however ambiguous it sounds. If one wants to draw general lessons from particularities or unusual historical events, one must be sure that they are repetitive and easily applicable upon other situations and in other contexts.

Even if trying to cooperate, Czechoslovakia got a poor lot by neighboring with Germany in the 30s, but that doesn't mean that the system as a matter of fact sucks all cooperative players that share border with defectors, nor that the neighboring great power is a priori a bad omen. It only means that some cooperators lose from time to time given particular circumstances. But overall, results point out that the effect of space and power falls equally on everybody and thus have a negligible influence with respect to the final rank. It was not a defecting great power neighbor, but lack of close enough friends together with surplus of eager rivals that cost Czechoslovakia its sovereignty. One can hardly imagine worse situation from the geographical as well as capabilities distribution point of view than that of the West Berlin. In 1948 and 1949 it was blocked and completely surrounded by the superpower's forces, yet it survived because there were still enough cooperators it could interact with. Similarly, in 1968 Czechoslovakia could not resist occupation by the Warsaw pact members because these very same countries were also players it interacted most often with. Relations to the West barely counted and the fact that the leader of Romania Nicolae Ceauşescu decided not to participate in the invasion similarly as Albania made very little difference since Bucharest and Tirana were isolated in their stance and frequency of their interactions with Prague was incomparable to the position held by Moscow. Friends (other communist regimes) turned enemies and enemies (Western countries) remained what they were. Surely, the same events can be interpreted using balance/bandwagon terminology, but hardly to the same depth, not to speak about the fact that we already defined these two foreign policy strategies in terms of defection and cooperation. From the individual player's point of view, it does matter *who interacts with whom and how often*. But overall it is much more important *how actors interact*. In other words, whether they are foes, or friends.

5.2. Full Model

Results of six different settings were examined with respect to the full model proposed in this thesis. Number of reruns of the program increased from 25 to 100 in order to achieve appropriate robustness, and that for both speeds (0.05 and 0.95) as well as all three levels of noise (1%, 3%, and 5% of both kinds). Below one can find described, analyzed, and depicted all the outcomes of 600 runs of the program in sum that used punishment payoff as the lower limit for payoff shift and all of the 70 already mentioned strategies. First I pay attention to the overall gains received, because they determine the rank of individual rules, and only then I move forward to distribution of mutually cooperative outcomes and interactions, either at the level of pairs, or with respect to corresponding averages achieved by particular strategies.

In harmony with what we found before, when we took a look at the impact of payoff shift in isolation from other variables, here also one can freely shift between both examined speeds without the slightest change of outcomes provided that other settings remain the same. It is important to keep in mind that for all three levels of noise, simulation results obtained by two various shift speeds correlated almost perfectly (*r* higher than 0.998). From new strategies' point of view and looking at the average rank of the rules, one should notice especially the restored success of GTFT. It finished first in the second baseline model, but faired much worse after inclusion of payoff shift. In the full model it proved its effectiveness once again thanks to its ability to cope with noise and ended up around 5th place under all settings. Clearly the worst performance was made by RANDOM. But surprisingly, Pavlovian rule WSLS did only slightly better than RANDOM. Under all circumstance it was able to secure gains sufficient enough only to always finish around 65th place in average.

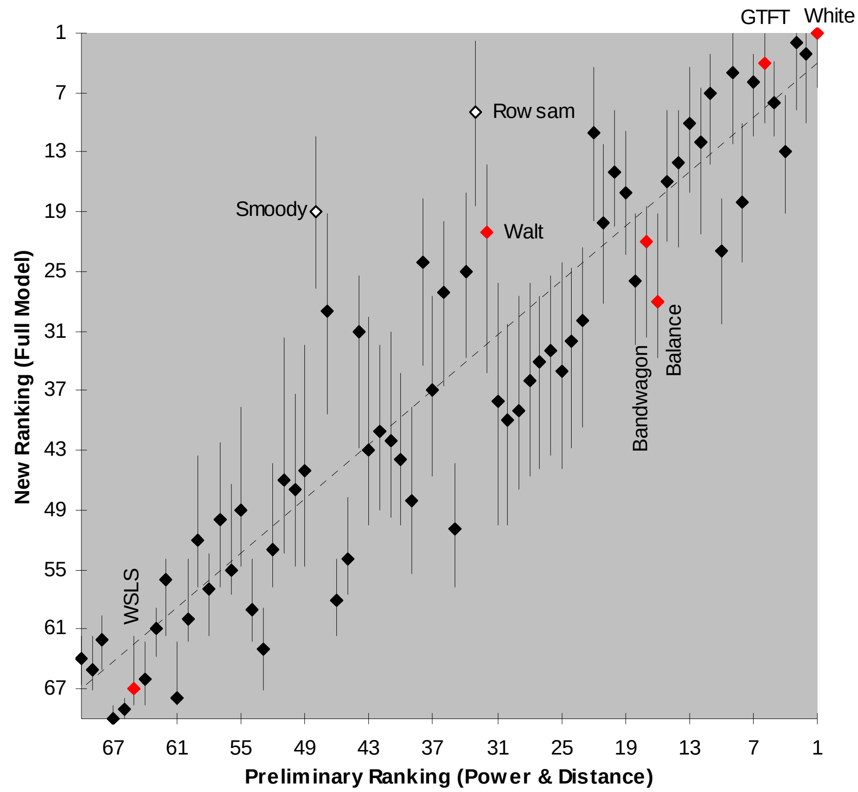

Figure 13: Full Model with 0.05 Shift Speed and 3% Noise of Both Kinds

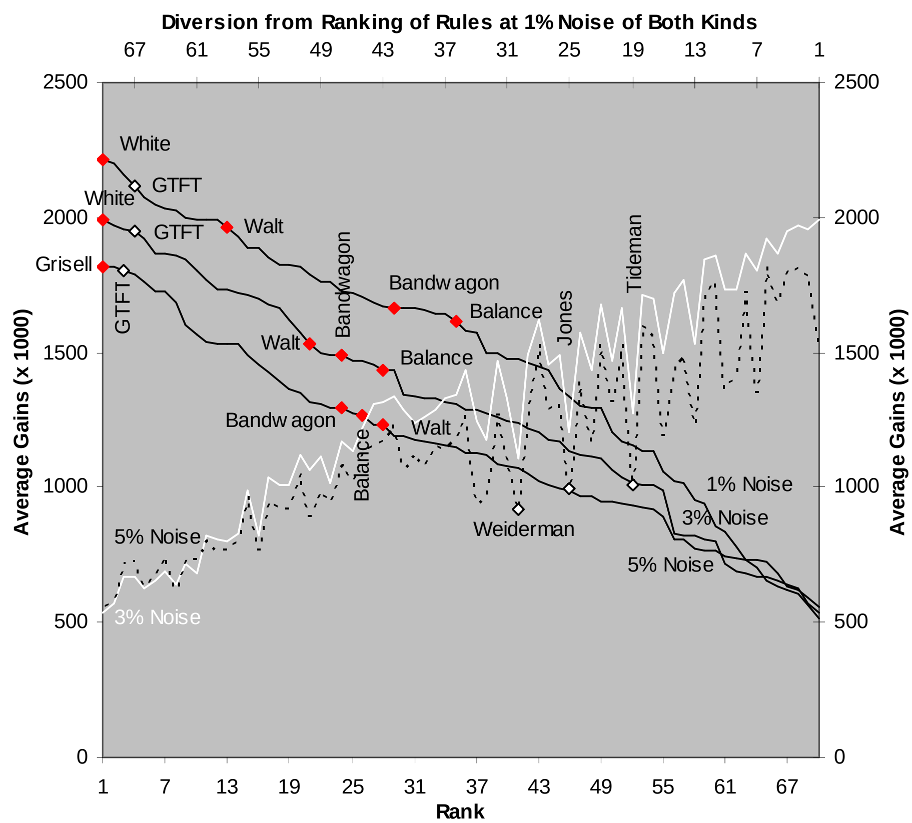

Figure 14: Full Model with 0.05 Shift Speed

Nice example of the situation is pictured on Figure 13. New ranking of the full model with 3% noise and 0.05 shift speed (y-axis) is compared with ranking received with help of the same settings but without any payoff shift included (x-axis). When comparing these two average rankings, only two strategies, ROWSAM and SMOODY, changed (improved) their respective position for more than 20 places, while the shift was close to 6 places in average for the whole population (correlations $r = 0.914$). On the other hand, ranking variability of individual strategies within 100 simulations conducted under the same full model settings remained at the relatively high level of 1/5 of the whole list, i.e. somewhere between the levels of individually examined power and distance variables. Notice also that besides two already mentioned rules, only three other strategies managed to improve their position more than WALT did. But with respect to three newly added rules trying to mirror usual behavior of states in the international relations system, it is another picture that would be more telling.

Generally, it is not that important at this point how particular ranking correlated with some previous results, because inclusion of virtually any level of uncertainty reshuffles original Axelrod’s ranking to a great extent, and I have already proved high correlation between his outcomes and those achieved by translated source code of the original strategies in a noiseless environments. What matters here is how to be successful and what are the characteristics of individual strategies that perform well. Figure 14 can help us with respect to that at least to a degree. It portrays results of simulations using 0.05 shift speed and different levels of uncertainty. First, notice the white line together with the black dotted one, both increasing from left to right. They represent average total gains (vertical axis on the right) achieved by individual rules given 3% and 5% noise respectively, but these strategies are simultaneously ordered according to the average gains received using the 1% noise of both kinds (upper horizontal axis). One can see two general tendencies. Impact of uncertainty upon less successful half of the population is much smaller than impact upon the more prosperous one. And second, rank changes easily identifiable by any downward turn of the white line after increasing the level of noise from 1% to 3%, are then only strengthened but not reversed or modified after further increase up to the 5% uncertainty of both kinds. This is clearly visible by the same shape of two mentioned lines and it enables us to focus on fewer levels of noise, if necessary. Dotted line also points out to diminishing success of the winning WHITE strategy under higher uncertainty (the very right end of both lines). Last but not least, there were three strategies, whose performance changed most as one increased the level of noise. Gains of TIDEMAN, WEIDERMAN, and JONES declined significantly as the uncertainty grew, and their positions dropped for 25, 24, and 20 places respectively.

Eight strategies were capable of winning at least one of the 600 reruns of the full model, but only three of them managed to do it under all six specific settings (see table below). Namely GTFT, repaired rule called CHAMPION, and EATHERLEY, all of them being also highly generous strategies forgiving many defections without retaliation. For example EATHERLEY starts with cooperation and defects only after opponent's defection, but with a probability equal to the ratio of other player's defections over number of all moves. CHAMPION on the other hand cooperates unconditionally in the first 10 rounds and then switches to tit-for-tat for another 15 moves. Thereafter, it defects only after other player's defection given the opponent has cooperated less then 60% of the time and the generated random number is bigger than adversary's rate of cooperation. It was, however, WHITE that achieved the highest overall average rank under four of the six settings. Only its poor performance given high level of noise made possible for GRISELL and CHAMPTION to become the most successful rules under 5% uncertainty with 0.05 and 0.95 shift speed respectively.

As already mentioned, GTFT faired by far the best from all newly included strategies. This can be seen also on Figure 14. Three black lines from the lower right to the upper left corner represent individual rules ranked according to average overall gains received (vertical axis on the left) given three different levels of noise. When analyzing impact of individual variables, inclusion of noise secured more gradual

Strategy / Settings	Shift Speed 0.05			Shift Speed 0.95			SUM
	Noise 1%	Noise 3%	Noise 5%	Noise 1%	Noise 3%	Noise 5%	
WHITE	56	41		71	38		206
CHAMPION	6	29	26	7	35	40	143
EATHERLEY	37	13	4	21	14	12	101
GTFT	1	14	34	1	7	1	58
GRISELL		3	31		6	38	78
YAMACHI			3			8	11
ROWSAM			2				2
TF2T						1	1

Figure 15: Winners of Simulations

change of received payoffs than was the case in a noiseless environment. Another effect of uncertainty apparent from Figure 14 is that increased level of noise is causing lower total gains achieved by almost all strategies except for the least successful ones. This is, however, nothing new. Although here it may be a bit overstretched, the statement that uncertainty is pushing other rules closer to haphazard pattern of behavior seems plausible, especially given the fact that RANDOM almost always finished last. Thus while under 1% uncertainty of both kinds the loser received in average only 23% of the winner's payoffs, under 5% noise it was already 30%.

Moreover, it seems that out of three new strategies mirroring behavior of states in the international relations system, higher levels of noise affect particularly badly the threats balancing rule called WALT. Its position falls back from relatively impressive 13^{th} place to a rather mediocre 28^{th}. Performance of BANDWAGON and BALANCE changed only a bit, but especially WALT was sensitive to greater levels of uncertainty. Difference between three international relations strategies gradually vanished too as the noise increased, which is quite interesting as well. Nevertheless, recalling the great success of BANDWAGON in a noiseless environment, when it finished second of all 70 rules after introduction of power and distance variables into the second baseline model (Figure 10), the poor performance of BANDWAGON in the full model justifies our earlier cautiousness with respect to its comparable advantages. Given the extent of the average gap between the winner and the loser, as well as given the distribution of total gains in general, both BALANCE and BANDWAGON must have used TFT strategy most of the time. Only few least successful opponents qualified for evoking different behavior from these two rules, and even this possibility gradually disappeared as the uncertainty became greater. Payoffs from the interactions with these least successful opponents also stand behind the slight difference in gains between BANDWAGON and BALANCE, which later narrowed as noise increased. Dominance of TFT choices in the behavior of BALANCE and BANDWAGON strategies is exemplified also by the fact that TFT itself, as an independent rule, ended up always between these two strategies that deliberately tried to reflect behavior of states governed by the power concerns only.

Since the gap separating BALANCE and BANDWAGON narrowed yet TFT still remained placed between them, it means that either because of the composition of the population, or simply because of the way how two rules were proposed and formalized, differences between these supposedly opposite patterns of decision-making gradually vanished as the uncertainty in the system increased. Basically the same happened to WALT, but thanks to complex nature of its behavior processes and of how it was turned into formal language of computer simulations, its performance is much harder to analyze deductively. The most plausible seems intuitive explanation that uncertainty hinders appropriate recognition of threats. WALT takes into account not only the probability of interaction with any given adversary, but also history of their previous encounters, which can be less straightforward precisely because of the noise. In such a noisy environment, lack of clearly recognizable patterns of interactions (and thus also threats) turns WALT ultimately into TFT rule. Similarly, diminishing differences of players' overall success (and possibly badly set thresholds) transform BANDWAGON and BALANCE into the same tit-for-tat copies.

Two following pictures can give us even more detailed insight into the nature of the population of behavioral rules examined in this thesis and in the full model itself. Let us focus first on the population as a whole. White line on Figure 16 portrays one particular distribution of interaction frequencies among all possible pairs of 100 players under 0.95 shift speed and 3% noise of both kinds (4950 pairs at the lower horizontal axis are ordered according to number of interactions as shown on the left vertical axis). It has also exactly the same shape as all other distributions of interactions under any of the six settings I used. In other words, neither speed of the payoff shift, nor level of noise, have any impact upon distribution of pairwise interactions in the population. Now this distribution is not uniform but it is very similar to the normal distribution. There are few pairs with very high frequency of interaction occurrence, and also some that interact rather rarely (compare the tendency with the very similar black line on Figure 4). At this particular case, the pair that interacted the most often did it on 8 274 occasions out of 10 000 possible. The least intense relationship was between two players that faced each other only in 1 432 rounds. It gives us a difference of 6 842 events between the most and the least frequently interacting pairs of players, yet 40% of this difference is covered by only 10% of the pairs (5% at both extremities of the distribution). Most pairs interact with a frequency close to mean value of 5044 encounters. Little more than 65% of the data (pairs) fall within one standard deviation of the mean and 96% are within two standard deviations. Corresponding values for normal distribution are 68 and 95%, thus making our data almost perfectly Gaussian.

Closer inspection makes this distribution maybe less puzzling. The fact is, that if interaction occurrence was based solely upon distance of players, distribution would have been of the very similar shape but ranging across the whole interval from 10 000 to

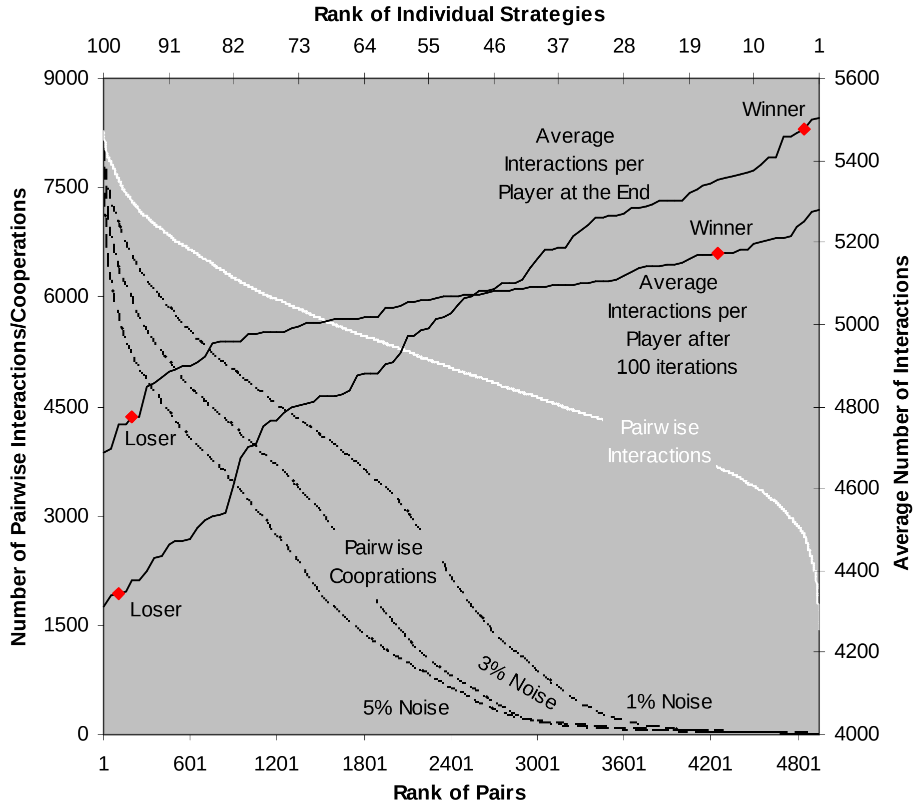

Figure 16: Distributions of Interactions and Mutual Cooperations (Speed Shift 0.95)

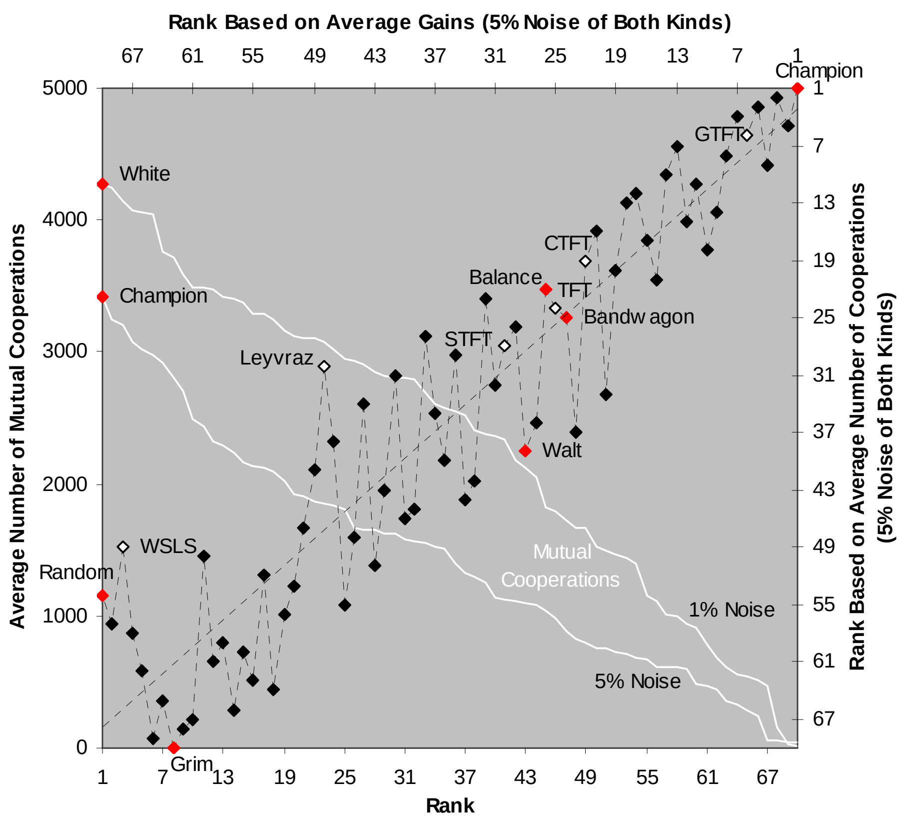

Figure 17: Average Mutual Cooperations by Strategies (Shift Speed 0.95)

0. Power variable thus influenced only the span between extremities, not the general shape of the curve. All players simply faced the same distribution of capabilities in the system and combined effect of their individual power variable values preserved the given shape. The same was already hinted when we examined impact of power and space in isolation from one another and found out that the final results (and thus also distribution of interactions) matched each other very well.

Situation completely changes, if we look at the distribution of interactions but from the individual players' point of view. This can be seen from the black lines rising on Figure 16 from the lower left to the upper right corner. They depict average numbers of interactions (vertical axis on the right) achieved by particular actors after the first and the last 100 iterations of the one particular game with 0.95 shift speed and 3% uncertainty of both kinds. Without power variable these curves would be simple horizontal lines, since space has the same impact upon all players in a closed square lattice and thus all actors would have achieved the same average number of interactions. Here it is therefore power that makes a difference. Initially, only the far ends of the lines become bended. Upwards in case of successful players and in an opposite direction in case of losers. At the end, however, the whole line becomes almost perfectly gradually decreasing with very good match between average number of interactions and success of a given player (r = 0.996). As far as it holds that the most powerful players interact most often, this is only understandable. But this match between gains and interactions develop only gradually as the pattern of binary interactions get settled (r = 0.895 after 100 rounds). It seems that distance has a greater impact at the beginning. The correlation between distribution of interactions across actors in the initial and the last hundred of rounds is rather low too (r = 0.596) as exemplified also by the positions of ultimate winners and losers.

To sum it up, neither on the level of pairs, nor at the level of players, does distribution of interactions resemble small-world or scale-free network. Among pairs the interactions are distributed normally, while among players their occurrence steadily increases as the player becomes more powerful. In neither case do interactions frequencies correspond to power law distribution as required by the small-world or scale-free networks. Moreover, connections (interactions) are not permanent but occurs and disappears in every single round separately, thus we must still work with averages, when analyzing their emergent structure. Probably more telling would be a distribution of mutually cooperative outcomes since remembering the history of previous interactions makes at least some place for continuity.

Mutually cooperative outcomes apparently demonstrate entirely different pattern of distribution than the white line depicting occurrence of interactions. Three specific simulations represented by the dotted black lines on Figure 16 used the same shift speed (0.95) as before and corresponding levels of noise are indicated on the picture as well. These lines neatly portray how the numbers of mutual cooperations (vertical axis on the left) in the population of individual pairs gradually decrease with increasing noise. And of course similarly as in the case of interactions they also illustrate the same tendency for other settings, since differences repeat across various shift speeds. From the shape of the curves one can also see that higher uncertainty uncovers and strengthens the differences between pairs with respect to their ability to cope with effects of noise. The greater is the uncertainty, the fewer pairs can maintain cooperative interactions, and the faster is the fall from high cooperativeness to the average or low numbers of mutually cooperative outcomes. Shift towards long tail power law distribution of mutually cooperating pairs is already visible, but it is still too far from being fully developed. It is therefore better to wait with conclusions until we examine another, less cooperatively biased population in control simulations, where we would not be forced to rely solely on extreme uncertainty.

What can be already said is that there is little or no correlation between number of interactions and number of mutually cooperative outcomes any given pair attains (r = 0.346 for that particular rerun with 0.95 speed shift and 3% uncertainty). This might be counterintuitive, but in fact there are many pairs in which players interact extremely often in spite of lacking mutual cooperations. They may simply be neighbors with high capability levels acquired from interactions with other players and not with that particular opponent. If you interact often with somebody else, it does not necessarily mean that your interactions are mutually cooperative.

However, Figure 17 at least indirectly shows that if you interact often with others, i.e. with all players of the population considered in average, you probably also often manage to secure many mutually cooperative outcomes from interactions with them. First, notice the white lines that represent average numbers of mutual cooperations (vertical axis on the left) for each of the 70 independent strategies achieved in 2x100 simulations under 0.95 shift speed and two different levels of noise. I did not use 3% uncertainty of both kinds since it appears to be just a transitory stage

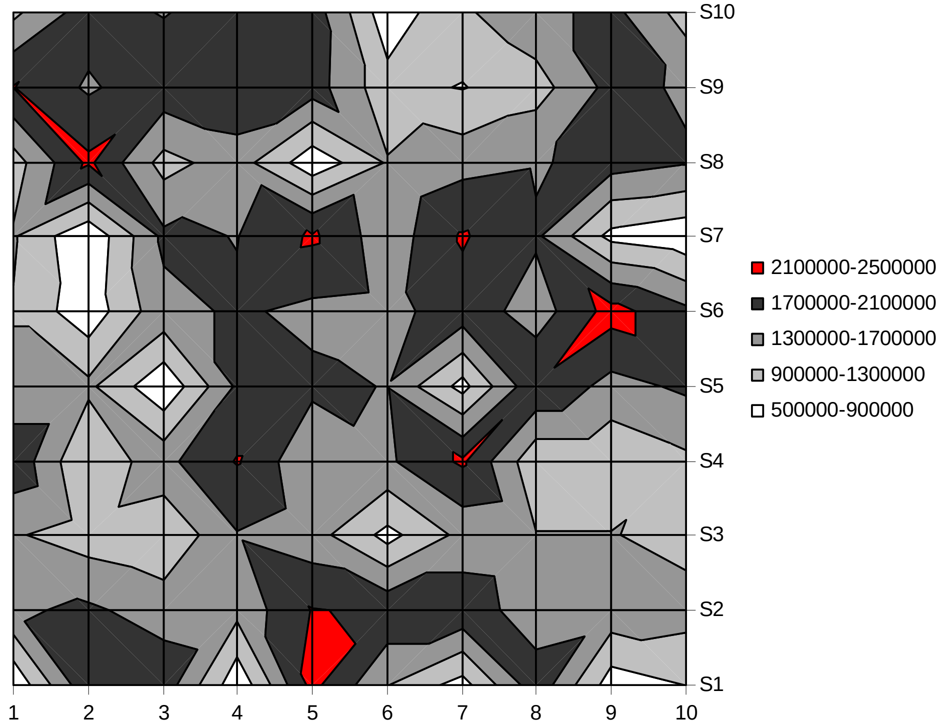

Figure 18: Playing Grid Distribution of Total Gains in the 50th Rerun under 0.05 Shift Speed and 1% Noise

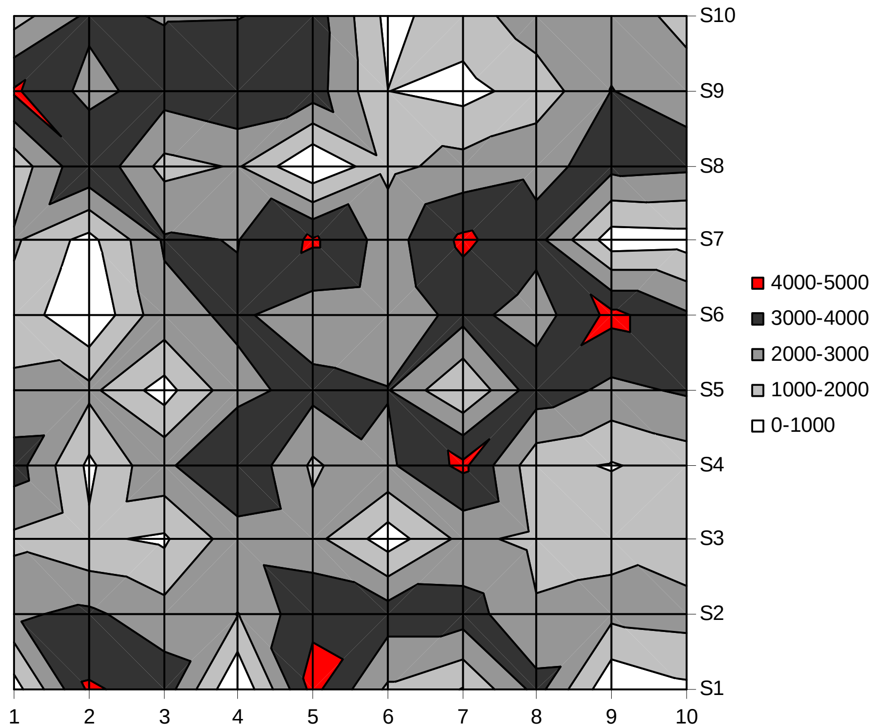

Figure 19: Playing Grid Distribution of Average Cooperativeness in the 50th Rerun under 0.05 Shift Speed and 1% Noise

whose full effect is developed under higher level of noise anyway. Those white lines indicates a significant drop in average number of mutual cooperation for all strategies as the noise rises with the only exception of the least successful players who simply cannot cooperate less. And although we can see that drop is not the same everywhere, gradual decline is still preserved fairly well thus avoiding any sudden drop even if one may still object a bit steeper fall at the far left.

Nevertheless, it is a dotted line from the lower left to the upper right corner of Figure 17 that should interest us the most. It portrays how two rankings, one based on average number of mutually cooperative outcomes (vertical axis on the right) and the other on average total gains received in 100 reruns (horizontal axis at the top), correspond to each other. The correlation is rather high (r = 0.936) with the most cooperative player being at the same time also the most successful (CHAMPION). This is not the case at the other end of the line, where unforgiving strategy GRIM secured the least mutually cooperative outcomes in average, yet fared much better with respect to gains. RANDOM did exactly the opposite with gains being much lower than suggested by the rank of its cooperativeness. Similarly poor performance as regards ratio of gains to cooperativeness achieved WSLS and LEYVRAZ. All three of them departed for more than 15 places, but the average difference between two rankings was of only little less than 6 places. The whole population remained spread close to the appropriate diagonal. There were, however, also rules that similarly as GRIM received higher gains than their cooperativeness implied. And one of the three new strategies formalized explicitly upon behavior of states was among those most successful in this respect. Only two rules in fact improved their final position more than WALT as regards average gains compared to average number of mutual cooperations.

For better understanding of the correlation between total gains and average cooperativeness (number of mutually cooperative outcomes) that particular players achieved, one may take a look at two pictures on the preceding page. They depict how these two indicators, i.e. gains in case of Figure 18 and average cooperativeness in case of Figure 19, were distributed at the end of one of my simulations. Here the game included 0.05 speed of the payoff shift and 1% noise of both kinds. And apparently, the same thing that I wrote above about all reruns of the 0.95 shift speed and 5% noise in general holds as well for this individual simulation with different speed and different level of noise. Two pictures are extremely similar and hence we can say that gains and cooperativeness are highly correlated independent of noise and shift speed.

Now, based on outcomes of simulations analyzed above, what can be said in short about the international relations system and the model proposed in this thesis? With respect to general characteristics of the system, it seems that power and space are much less important than amity and enmity emerging out of the previous interactions. Impact of the former upon success of strategies is small, if not nonexistent, while the latter proved to be consequential. Of course, particular situation always matters. CHAMPION, the overall winner of simulations with 0.95 shift speed and 5% noise, can still end up ninth. GTFT as the most successful new strategy can finish first but also 16th given the particular circumstances, and all that under the same setting of key parameters. Similarly, WALT can manage to be 23rd, but also 62nd in a pool of 100 competing players. But I am not interested in some peculiar circumstances under which even the loser can become a champion. I care about what system facilitates, and which features have significant effects upon performance of actors. Space and power appears not to be among them, in contrast to the possibility of friendship and enmity.

Two other findings are interesting with respect to the system as a whole. First, only few pairs demonstrate extremely high frequency of interactions but these at the same time do not necessarily have to be cooperative in nature. This can be easily illustrated by interactions of great powers. Most of the pairings, however, exhibit interaction frequency within one standard deviation from the average in the population, which basically equals to half of the possible opportunities. And again only very few pairs rarely interact at all. Second and probably more important finding deals with the average number of interactions, gains, and mutually cooperative outcomes that given strategy is capable to achieve. Naturally, the higher total gains one gets, the more it will interact in the future with other players and the more interactions it had to execute in the past too. But it also holds that higher average gains or greater average frequency of interactions usually indicate more mutual cooperations present in the history of that specific player's encounters. In other words, player that interacts frequently with almost all other actors, yet rarely on a cooperative basis, would not be ultimately able to do that for long without negative impact on its capability level. Simply, if you want to prosper (get high payoffs) in the international relations system, you have to cooperate.

As regards individual strategies used in the full model and their particular characteristics that were most effective in guaranteeing overall success, it seems that generosity is the right answer under most circumstances. In form of various strategies it constitutes an appropriate way to ensure mutual cooperation and thus also victory.

Generosity pays of very well in a cooperative environment, where defections are mostly caused by uncertainty rather than by deliberately chosen non-cooperative behavior. Out of the three behavioral rules that ought to mirror the conduct of states in the international relations system, WALT stood out as the most promising one. The best it managed to achieve was 5th place under 1% noise of both kinds, but its performance gradually worsened and approached that of other two international relations rules. Few hints, nevertheless, suggested some advantageous qualities of WALT. Accidentally, they fully developed only under control simulations that I conducted for completely different reasons in order to ensure that my results are not overly conditioned by the composition of cooperatively biased population of Axelrod's strategies.

5.3. Control Simulations

I realized the predominantly cooperative nature of strategies used in the full model for the first time during translating of the original source code of Axelrod's strategies from Fortran into C#. Then, as I analyzed outcomes of simulations, this impression only strengthened and I was therefore more than willing to use some other composition of the pool of available rules, when this opportunity arose. The best option appeared to be the one used by Nowak and Sigmund in many of their simulations (see e.g. 1993).[6] Players in their models remembered only how the very last round terminated and they cooperated or defected after each of the four possible outcomes according to four probabilities from 0 to 1 randomly ascribed to them at the beginning of the game. Thus for example GRIM would be formalized as (1, 0, 0, 0) because it cooperates with probability 1 only after mutual cooperation (CC) and defects otherwise. TFT would look like (1, 0, 1, 0) since it cooperates after receiving reward payoff and also after own unilateral defection (DC). Finally WSLS would appear as (1, 0, 0, 1) thanks to its naïve willingness to cooperate after mutual defection.

For the first 25 of the control simulations that assumed 0.95 shift speed and 1% noise of both kinds I therefore formalized new VIENNA behavioral rule named after the city that Nowak and Sigmund originally came from. Four probabilities determining cooperativeness after each of the four possible outcomes were randomly and separately chosen for all players using this strategy at the start of the game and then rounded to one decimal place. Decision in the first round was made as if it was preceded by mutual cooperation. I used ten different strategies in this control simulation setting. Besides

[6] I am thankful to Lars-Erik Cederman for turning my attention to this possibility.

VIENNA I also included three strategies inspired by the behavior of states, Pavlovian WSLS (because it was successful in simulations by Nowak and Sigmund), and the five most successful rules from the full model simulations analyzed above, namely WHITE, EATHERLEY, CHAMPION, GRISELL, and GTFT. There were 100 players as before. Nine of them got strategies already known from the previous simulations and the remaining 91 actors received copy of the VIENNA with unique four probability values. For reasons of simplicity, I sorted all 14 650 possible strategies into 90 categories during the processing of acquired data. More precisely, 11^4 new rules were arranged into 3^4 distinct groups by way of reducing 11 available cooperation probability levels (decimal numbers between 0 and 1, including) after each of the four possible outcomes into three different intervals (probability of cooperation greater or equal than 0.7; less than 0.4; and the rest).

All 25 reruns of this control setting were won by WALT. To correctly interpret this result we need to remember that the new pool of strategies is probably the most heterogeneous population we can achieve given constrains of additional extension of players' memory. From the black line on Figure 20 one can clearly see how average gains of individual strategies (see the vertical axis on the left) sharply decreased right after the winner. The second most successful strategy (GRISELL) received only 90% of the winner's payoffs and this rapid decline leveled only later to some extent. When compared to gradual and relatively even decrease in case of lines on Figure 14, this suggests that success in control simulations is a much more fundamental phenomenon achieved only by very few and probably requiring some specific qualities too. In fact, all of the old rules finished in the top sixth of the final list of strategies. But rather than implying necessary success of more complex rules that take advantage of longer memory, it only underlines effectiveness of the previous preselection. For example GTFT (4^{th} place) and WSLS (8^{th}) can be easily regarded as examples of VIENNA rule. Moreover, there were several newly generated strategies that ended up very high. For instance the least cooperative group of rules with four assigned probabilities lower than 0.4 finished third and secured 78% of the winner's gains in average. On the other hand, when looking at the total sum of gains, the least successful players received relatively higher total payoffs than under the previous settings (40% of the winner in control simulations compared to 30% in the full model).

Yet not only general distribution of total gains was different from what we saw previously. Various paths toward success seem possible as well. GRISELL, the second

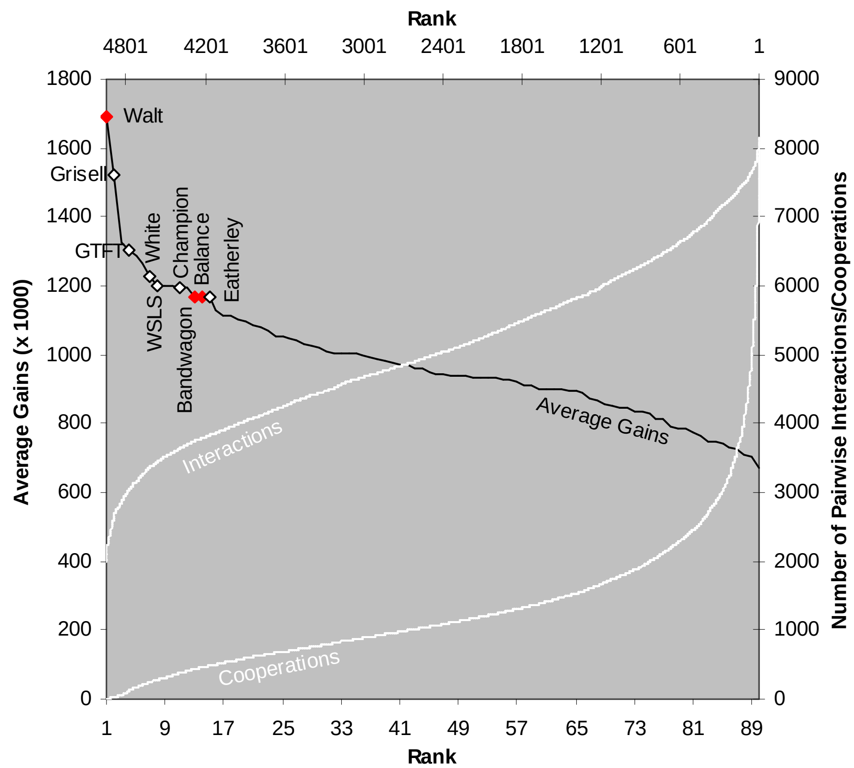

Figure 20: Vienna Control Simulations (0.95 Speed and 1% Noise)

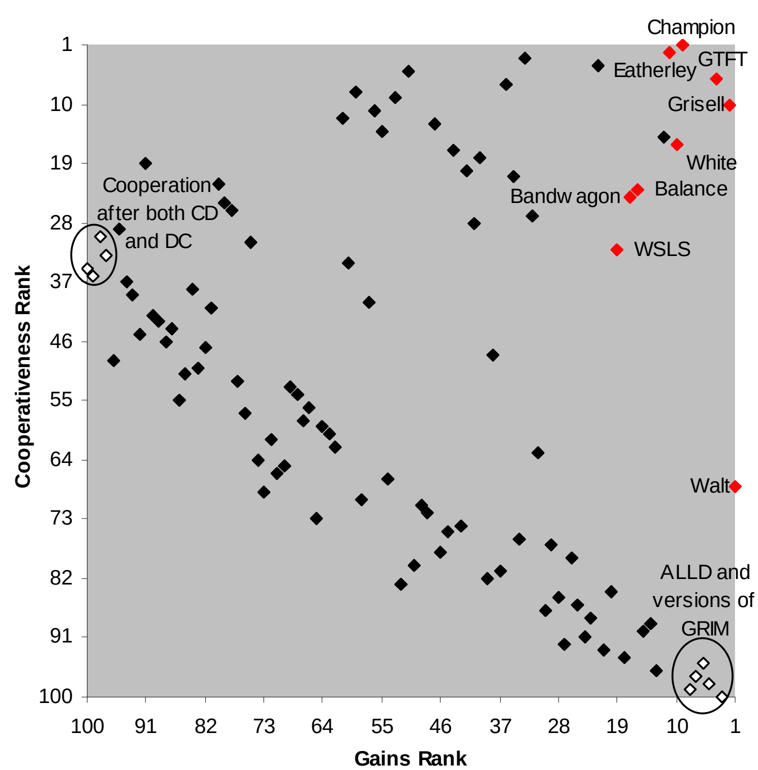

Figure 21: Relationship between Cooperativeness and Overall Gains

most prosperous rule under the considered control setting, in which it moreover never ended up worse than fourth, cooperates if the number of opponent's defections is less than half of their interactions. It is therefore not a simple generous strategy that forgives defections with a given probability. Rather, it is fully deterministic rule that completely disregards non-cooperative behavior provided that the other player cooperated enough in the past. Adversary must therefore constantly fulfill certain conditions in order to profit from the first player's profound benevolence. GRISELL in a way examines the presence of threat similarly like WALT based on previous interactions, but at the same time it pays no attention to power or distance. The third most successful behavior, however, was the one by group of players similar to ALLD rule as mentioned in the preceding paragraph. Still other qualities characterized fourth rule, namely GTFT, and also WSLS fared much better than in the full model. GRIM-like versions of VIENNA rule that cooperated with high probability only after mutually cooperative outcomes then ranked ninth in average, while group of strategies similar to ALLC that cooperates unconditionally ended up at the 45th place.

Although one can see some tendency that the greater is the average willingness of player to cooperate after all four possible outcomes, the lower is the chance of being successful in the population used in the control simulations, another fact is more telling in this place. We already defined and used cooperativeness in terms of ability to secure as many mutually cooperative outcomes as possible. And its correlation with overall level of gains vanished entirely here. Cooperativeness was no longer synonymous with success. Taking as an example the last one of 25 control simulations under present settings, the correlation between the average number of mutual cooperations and the overall sum of gains is -0.241 and without any simple, clearly recognizable pattern (see Figure 21 above). WALT, strategy that received by far the highest total payoffs, was only 68th with respect to average number of mutually cooperative outcomes of interactions it participated in. And many others followed the same path. As with the previous data, I expected individual players to be distributed along the straight line from the lower left to the upper right corner, but results suggest instead that the higher is the number of mutual cooperations, the lower is the rank attained. This holds at least until certain threshold being surpassed, after which the ranking increases again. In fact, WALT is the only one of 9 old strategies not belonging to the upper right quadrant on Figure 21 and yet it is still the most successful one.

Of course, it is possible to get a bit deeper insight into the impact of four VIENNA probability values upon overall success, and we can also try to get better statistical understanding of how the gains/cooperativeness relationship evolves. But our goal here is merely to examine the performance of nine old strategies in a different pool of rules. From this point of view, one is perplexed by two facts in particular. First is the lack of similarly straightforward relationship between level of gains and average cooperativeness as was present in the full model data before. This is best illustrated by the extraordinary success of balancing against threats that cooperates very cautiously.

WALT not only cooperated with nice players and defected against the mean ones, but it also took account of power and distance. This made possible to recognize among its opponents those with whom it would interact most often. Subsequently, WALT was willing to unconditionally cooperate and risk extensively only with the least frequent opponents and it took more cautious stance in case of intense interactions. In a pool where most players are nice and cooperative, this makes little difference. If most of the guys around you are friends, it is only natural that the most frequent partners would also be friends, and that it is futile to be cautious towards them. When there are not enough defective players taking advantage systematically of overly cooperative actors, recognizing mean neighbors is rather superfluous. However, in a highly heterogeneous population, the one in which distribution of actors on the playing grid makes also a bit greater difference as regards results of individual simulations, WALT achieved victory precisely thanks to its ability to see the threats accurately. Being cautious pays off when you are surrounded by not only friends, but also many foes.

The second perplexing fact is distribution of both interactions and mutually cooperative outcomes across individual pairs of interacting players as portrayed by the white lines on Figure 20 (see the vertical axis on the right). Similarly as before, also here the closer inspection reveals that normal distribution characterized frequencies of encounters in 4950 possible binary combinations that hundred actors gave rise to (upper horizontal axis). Yet the distribution of mutually cooperative outcomes was a bit different from what we saw before. Even though I used only 1% noise of both kinds in these control simulations, tendency of cooperative outcomes to approach the power law distribution at the level of individual pairs was even more obvious than under the full model with 5% noise of both kinds. In this case the tendency was therefore not caused by uncertainty but rather by heterogeneous nature of the environment with many defecting players. In other words, only small number of pairs managed to sustain frequent and cooperative interactions, while overwhelming majority of them backslid into only occasional cooperation (population average was 1287 events) relative to number of interactions (population average was 5081 events). Unfortunately, not even this fulfilled the requirements of small-world and/or scale-free networks as defined by the average distance of nodes and number of their connections. Even if distribution of mutually cooperative outcomes did correspond to properties of such a network, it would still probably be an overstretched argument, since this special kind of interaction structure ought to facilitate and stabilize cooperation itself. Cooperation should not be a point of departure, but rather an end state, a consequence of such a network

At the same time, however, in all of the first 35 most cooperative pairs in this particular simulation, i.e. in those pairs with the highest number of mutually cooperative outcomes, at least one side of the dyad was occupied by some of the nine old strategies preselected with help of the full model. Not to speak about the fact that 18 out of these 35 cases contained the preselected strategies on both sides of the dyad. These few pairs representing less than one percent of all dyads moreover covered almost one third of the whole interval between the most and the least cooperative extremities. What is even more remarkable, threats balancing WALT rule that won control simulations despite its low average cooperativeness ratio figured prominently among these highly cooperative dyads, thus further stressing its ability to recognize friends and foes. And since the similar facts can be found in data from other reruns given the same control setting, I am not generalizing here from some accidental results.

As we already know, average gains and average cooperativeness no longer correlated with each other at the level of individual players, but some of the most successful actors (at least those preselected in the previous simulations) were still able to sustain highly cooperative and extremely frequent interactions among themselves. In a way, they formed some kind of cooperative group in a highly competitive and rather non-cooperative environment, without necessarily sharing a border with each other. It thus follows that even if there are different ways how to secure success in a highly heterogeneous population, being a nice but not unconditionally cooperative guy apparently leads over time towards discovery of the right path through the maze that ultimately brings other players of this kind together. Ability to correctly estimate who are your true enemies can only help in such a situation. Because cooperation gives both players in the binary Prisoner's Dilemma higher payoffs than mutual defection, this path also appears to be a bit more sustainable than simple unconditional non-cooperative

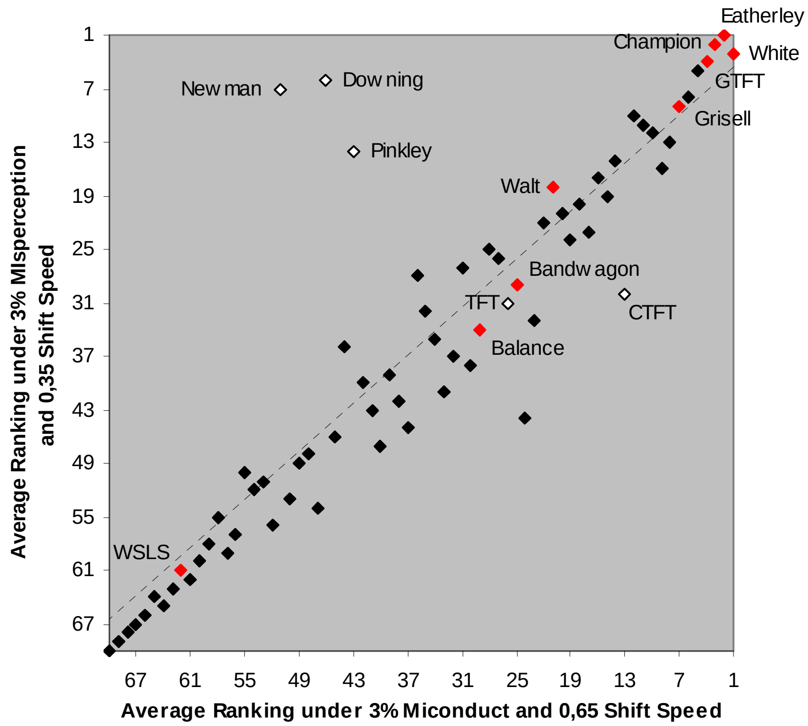

Figure 22: Correlation between Results of Two Other Control Settings

behavior. One can hardly find a better example of such a loose group of not necessarily neighboring players using various but cooperative strategies than was (and still is) the North Atlantic security community as described by Deutsch (1969) and comprising all its extensions in other regions such as the Pacific Basin and the Southern Hemisphere.

Simulations that included VIENNA strategy were not the only test of robustness of the full model results that I conducted. Two other settings proved that my data and outcomes did not suffer from exclusion of certain values of some parameters. As is already known, the full model settings included both misperception and misconduct, worked with punishment payoff as the lower margin for mutual cooperation reward shift, and focused upon 0.05 and 0.95 shift speeds. Thus in the last two control settings I opted instead for a different lower limit of the payoff shift now computed as an average of temptation and being a sucker. Furthermore, two remaining values of the shift speed were examined similarly like the separate impact of individual uncertainty effects. To be more precise, 0.35 shift speed was coupled with 3% misperception probability (y-axis on the figure above), and 3% chance of misimplementing one's own decision joined the 0.65 shift speed (x-axis on Figure 22). Simulations with both designs were run 25 times again.

Similarly as before, it holds also with respect to Figure 22 that the closer are players distributed along the diagonal from the lower left to the upper right corner, the higher is the correlation between outcomes of the last two control settings. Here the tendency is clearly apparent and dotted trend line portrays it perfectly. High level of the average ranking correlation (r = 0.895) stressed the fact that actually both the separate inclusion of misperception as well as that of misconduct ultimately led to the very similar results. Without the rules in the upper left quadrant (see the three white dots most removed from the trend line) the level of correlation between effects of misperception and misconduct would be even greater than 0.974. Under both settings the five most successful players identified in the full model simulations were remarkably prosperous too (see the red points grouped in the upper right corner).

One of the very few surprising results of these final control simulations was rather unexpected success of three strategies (PINKLEY, NEWMAN, and DOWNING), which, however, happened only in an environment with limited misperception. They did not manage to repeat this performance anywhere else. Neither small misimplementation probability, nor the noiseless setting proved to be so helpful in securing high payoffs for these three rules as the environment with possibility of misunderstanding did. Part of the reason behind that might be the fact that they all estimate the nature of opponent's future behavior based on his/her previous responsiveness to cooperative/defective moves. Unlike misconduct, misperception enables that some strategies paying attention to opponent's responsiveness swiftly change their pattern of behavior in specific circumstances of abundant defections. Within those three decision-making rules, the occurrence of misperception usually affects only one specific variable while others remain intact and can shift abruptly when finally activated. This stormy development can easily restore mutual cooperation. Inclusion of misconduct affects more parameters simultaneously and therefore prevents any turbulent phase from occurring.

Not much has changed in other aspects from what we have already seen in the full model data. Three rules that mirror behavior of states in the international relations system all ended up at approximately the same position as in the previous reruns with at least comparable level of noise. This holds also for Axelrod's winner TFT and for Nowak's and Sigmund's Pavlovian WSLS rule. When we take a look at the correlation of control simulations with the results from the full model, then we get similarly high degree of similitude as on Figure 22. Outcomes of the full model setting with 3% uncertainty of both kinds, 0.95 shift speed, and punishment (P) as the lower limit for payoff shift correlates with results of two control settings at the level of 0.914 and 0.970 respectively for misperception and misconduct applied separately. When compared to data from the full model setting with 0.05 payoff shift speed, then the correlation coefficients of the last two groups of 25 control simulations considered here remained virtually the same too. In other words, very little if anything would have changed in the full model results, if I had employed in my model other margin for payoff shift, both uncertainty effects separately, or even different shift speeds.

Control simulations thus did exactly what is usually expected of them to do. They showed when the results hold and when we need to be more cautious. Balancing against threats proved to be effective in an environment, in which distinguishing friends from foes becomes crucial and where there are at least as many defectors as cooperative players. There is no need for such a capacity in a milieu without enemies, where non-cooperative behavior is just a matter of misunderstanding or misperception. On the other hand, given the population used in the full model simulations very little could have been gained by doing more reruns with different settings than I examined.

6. Conclusion

Lamenting about the state of systemic thinking in international relations theory in recent years, Albert and Cederman (2010: 2) stated that it is in fact the extremely interconnected character of the system itself in our days that requires precisely the kind of missing systemic perspective in order to grasp its structure and dynamics. They even mentioned complexity theory as a possible candidate for renewal of systems theorizing. This thesis is an attempt to model international relations from this point of view.

I didn't try to formalize interactions during the Cuban Missile Crisis or any other historical event. My attention was not focused upon particular region or state. Neither did I seek to replicate the distribution of power in the present system of states with preeminent position of the United States, the rising star of China, and carefully advancing European Union. I already wrote in the introduction that my aim is to inquire into the consequences of the system. My intention was to model how the system works, and not where it is in the present moment. Instead of analysis of the real world data in order to recreate only the current settings in the world affairs I thus started with theory.

In their accurate description of the state of affairs Albert and Cederman pointed out that the rationalist and individualist approach of strategic choice exemplified by game theory dominated mainstream from the late 90s further on and overtook the power from structuralist theories such as realism. This prevailing individualism also brought about and was responsible for the lack of systems theorizing. However, they did not explore in detail the connection between rationalism, neorealism, and game theory as for example apparent in the case of neo-neo synthesis. I decided not only to cope with the problem of individualism in the rationalist thinking, I moreover did it by trying to bridge the gap between constructivism and neorealism with help of agent-based modeling. I believe that similarly like in ontological matters, the related multi-agent simulations in case of epistemology and methodology can also take a middle position (now between quantitative and qualitative methods) in exploring the complex systems.

This may seem a bit over-eclectic attitude, but as far as I am not proposing a new theory, it seems only pragmatic (Friedrichs – Kratochwil, 2009: 708-9) and beneficial to include in the model insights from various vantage points that existing theories of international relations offer.

> [I]t is only because of the politics of knowledge in the discipline … that we argue over whether scholars have violated their supposedly all-important allegiance to their theoretical aggregates if they combine

> variables and mechanisms associated with different schools of thought. (Jackson – Nexon, 2009: 920)

And thus I built the model as I did, by attempting to formalize the way how different cultures of anarchy rise up out of players' interactions, by stressing the common points between agent-based modeling and constructivist emphasis on rules, agents, and structure and on constitutive relation of the last two, and by trying to improve the realist understanding of the system and its structure dating back as far as to Hobbes. Ultimate form of the full model is rather complex combination of power, geography, uncertainty, payoffs, agents, and their mutual (dis)trust created over huge number of repetitive interactions. However, from the international relations theory point of view the most important is the formalization of constructivist argument by way of payoff shift, inclusion of power and distance as factors determining interaction occurrence, and mathematization of three strategies mirroring the behavior of states. I hope that combination of all these different variables and features makes sense not only theoretically but also intuitively.

Of course there are many aspects in the system of international relations that remained unexplored in my model, and which legitimately ask for further attention and inquiry. Formation of multilateral alliances with help of other mechanism than just that of cooperative binary interactions causing mitigation of the Prisoner's Dilemma might require modification of several key assumptions. For example frequent interactions with one player may directly affect probability of interactions with some other actor and thus not only condition the impact of distance, but also facilitate emergence of truly *social* culture of amity and enmity at the systemic level. Control simulations also suggest that population heterogeneity as achieved by inclusion of VIENNA strategy can bring about some new findings in the future as well. Learning, possibility of some evolutionary path, and other ways of changing players' strategies then require more detailed consideration before taking into account too. Similarly there are many possible ways how to further develop already present features of the model or alternatively to add others, already formalized in different research designs. These features are not included in my model simply because I understood them either as superfluous and not important enough to further complicate the model, or because they just did not demonstrate equal influence upon all players giving me no reason to add them at the systemic level. I have in mind especially some kind of universal forgetting parameter as regards previous interactions (Ashlock – Smucker – Stanley – Tesfatsion, 1996) and varying speed of the payoff shift depending on who interacts with whom and how. Nevertheless, my results proved to be interesting enough even without these additional features.

The basic research question asked what consequences have properties of the international relations system as regards prospects of cooperation among states. It was Robert Axelrod who showed that the Prisoner's Dilemma does not necessarily means ever present defection. The fact that I successfully replicated triumph of TFT rule under the original setting thus only corroborated that his Fortran source code was properly translated into C#. But already slightly modified parameters with more iterations and no interactions with one's own copy led to victory of GTFT even in absence of any noise. This generous extension of tit-for-tat was willing to offer more cooperation than it received in return. Many Prisoner's Dilemma models, however, lacked features often perceived as crucial for functioning of the international relations system and thus plausibility of their cooperative outcomes might have been questioned. But neither power nor distance (included separately or together) changed in any noticeable way the overall ranking of strategies that we got using the round-robin pattern of interactions. It was only shift of payoff matrix that finally made a difference.

At this point it was still not the question who wins and when, but rather what is the impact of individual variables. Most importantly, power and distance, i.e. structural variables at the systemic level of analysis, had no impact upon results whatsoever. A non-structural systemic phenomenon of noise of course influenced the outcomes, but again there was no difference between noisy round-robin and noisy power/distance settings. Instead, it was inclusion of factor that governs mutual shaping of actors and structure via history of interactions that wielded significant influence over outcomes of simulations. In other words, it is not the structure that matters but actors and especially their interactions leading to friendship and enmity.

If we focus our attention upon results of the full model proposed in this thesis, then several general findings arise as well. First, different levels of uncertainty and different speeds of making friends/foes do make a difference, even if not a great one. Increasing noise for example brings about lower overall gains, diminishing cooperativeness, smaller differences between winners and losers, and slight reshuffling of the victorious players. Second, there is a strong relationship at the level of actors between average number of mutually cooperative outcomes given player is capable to secure, and overall gains (s)he received. In other words, to be successful one has to cooperate. Furthermore, natural correlation between overall gains and number of player's interactions only improves over time too. Development of greater differences in capabilities strengthens the effect of power upon interaction occurrence compared to more evenly distributed systems, where distance might play a bigger role. Hence, at the end we can say that gains, cooperativeness, and interactions are basically synonymous.

Third, neither distribution of interactions nor that of cooperative outcomes corresponds to scale-free or small world distribution. Neither at the aggregate level of players nor as regards their base level of binary combinations. Frequency of encounters in individual pairs follows normal distribution, while distribution of mutual cooperations in individual pairs only gradually gets closer to power law distribution as uncertainty increases. In contrast with what we found at the level of actors themselves, even very intensive binary interactions do not necessarily have to be cooperative in nature. In the real world great powers also interact very often but there is no sign indicating that these interactions must be cooperative. We should also not forget about the great variability of final positions, which is caused by the particular distribution of actors on a playing grid. From given player's particular circumstances point of view, it does make a difference whether your neighbor is Nazi Germany or Switzerland.

Yet what shall interest us here are not particular cases, in which even nice guys might be doomed, but general tendencies instead. With respect to that, you've got a fair chance not to be at the losers' side as far as you cooperate. Irrespective of your neighbors or how powerful they are. That is because all five most successful rules in the full model simulations were extensively generous and made much more cooperative moves than was the amount they were satisfied with in return. It is also because the more mutually cooperative outcomes you were able to secure in average during many rounds of the game, the better you fared at the end. Despite all this, you as a cooperator may eventually lose, which is disappointing. But others like you would win anyway. The system does not favor defective players but cooperators.

Now what if one faces different pool of players with not only friends but also many enemies? Even in such conditions cooperating actors that won full model simulations achieved the highest overall payoffs. And surprisingly, the balance of threat strategy formalized according to theory originally developed by Stephen Walt won by a large margin. In a highly heterogeneous environment it thus seems profitable to be cautious. This rule was generous only towards cooperators, while defecting opponents received less than a fair share of cooperative moves in return. The extent of these two groups was further influenced by the probability of interaction occurrence, so that less frequent encounters induced greater generosity. And even though average level of cooperativeness was no longer correlated with overall gains, mutually cooperating players still found their way to each other.

To make it as clear and simple as it gets, I am not trying to say that wars can be eliminated in the future. The point is rather that non-cooperative behavior is obviously not the best strategy how to achieve prosperity and security. Norman Angell (1913) said a similar thing, but his writings were derogatively simplified into jokes about naïve idealism. War and defection can be of course still easily present in the system. But results show that the system favors cooperative behavior. Even if defection might be beneficial under some conditions, cooperation prevails at the end. Even if the international relations system deteriorates in the future back to the long period of war struggle as was in fact the case during most of the human political history, properties of the system formalized in the proposed model will hardly change. The system, or rather gains resulting from players' encounters, would eventually lead political actors again towards cooperative pattern of interactions. If anything, war is only the starting point, the beginning, or rather the childhood of international relations system's development path. The end is cooperation, not war.

I perfectly realize that there is only one world you can draw implications from. But simulations are here precisely in order to find out, to what extent is this world just a matter of chance, and to what extent it corresponds to the most probable scenario. What I did is ultimately just a model often relying on intuitive plausibility of its assumptions and thus always in question of its real-world relevance. But there is no other way how to find out what the system enables and prevents. And if we don't find it out, we won't get familiar with the reality we've got, thus making it much harder for us to respond to it. Using inference to the best explanation, if the model is right, then generous cooperation in the international relations is not a passing occasional phenomenon in otherwise ruthlessly defecting environment. If the model is right, then it is trust and not power or distance that makes a difference. If the model is right, balancing against threats is the best way how to cope with an environment in which there is only limited number of nice guys. If the model is right, it is not the systemic level but the level of states' interactions that must be looked at for causes of war. Simply, the war is not here because of the system. The model was at least somehow able to explore the real world issue of cooperation among states. Hence, there is some reason to believe that it is right.

QED

7. Appendix A

Bugs in three strategies were discovered after all simulations were done and the analysis of their results finished. These wrongly formalized rules were CTFT, REMORSE, and WEAKLING. Only former two got into simulations, while WEAKLING remained similarly like rules from the Axelrod's first tournament outside the pool of strategies involved in individual reruns of the program. All of them use not only outcome of the previous round but also the so called standing of both actors in order to determine one's own behavior in the present iteration. This standing can be either good or bad.

What I did is that I rewrote these rules in a way that players using them would need to consider only outcome of the corresponding previous interaction and one's own standing. In other words, they would not need to pay attention to other players' standing any more and this would also prevent possible confusion in case of misperception occurrence. Since this particular effect of uncertainty can be understood either in form of misperceiving opponent's last move or alternatively as misperception of adversary's standing only, excluding opponent's standing from necessary considerations prevents this confusion at its roots. On the other hand, it requires three types of standing (content, provoked, and contrite) instead of only two.

Shift from two to three different variants of standing was part of the problem with respect to those above mentioned strategies. Good or bad standing is determined after player makes a move in the current round, i.e. not after taking a decision but instead after taking an action. Possibility of misimplementing the decision is examined before setting the final standing and thus mistakes are reflected in it. In contrast, standing that has three variants is determined before any action takes place. Player becomes content (C), contrite (R), or provoked (P) based on outcome and own standing in the last round. Only then it can make a decision, take an action, and possibly even misimplement own choice. But neither of this has then any impact upon given standing in current iteration. Translating between two designs of actors' standing formalization requires some attention to detail and I apparently lacked that when I was doing it.

In a good/bad standing environment, player gets good standing after cooperative move or alternatively after defection provided that it was in good standing in the previous round while the opponent was in bad. Now three above mentioned rules can be described as follows: CTFT always cooperates except in the case that it was in a good standing in the previous round and opponent was in a bad one; REMORSE cooperates after mutually cooperative outcome or if being in a bad standing; and finally

WEAKLING cooperates only if it is in bad standing. The mistake present in WEAKLING is simply that I formalized it in a way that it starts with cooperative move instead of defection. However, this strategy appeared in no simulation, so this bug has no effect upon results whatsoever.

Given the possibility of three different variants of standing, the logic of contrite TFT rule can be summed up by the following few sentences. This strategy defects only if being provoked, and it gets provoked after being a sucker in the last round while content or provoked, or after receiving punishment payoff while simultaneously being provoked. It becomes/remains contrite and cooperates, if in the previous encounter it defected while contrite, or if it got temptation payoff while being content. In all other 6 cases[7] it becomes content and cooperates.

1.	After "CC" while content:	stay content and cooperate
2.	After "CC" while provoked:	become content and cooperate
3.	After "CC" while contrite:	become content and cooperate
4.	After "CD" while content:	become provoked and defect
5.	After "CD" while provoked:	stay provoked and defect
6.	After "CD" while contrite:	become content and cooperate
7.	After "DC" while content:	become contrite and cooperate
8.	After "DC" while provoked:	become content and cooperate
9.	After "DC" while contrite:	stay contrite and cooperate
10.	After "DD" while content:	stay content and cooperate
11.	After "DD" while provoked:	stay provoked and defect
12.	After "DD" while contrite:	stay contrite and cooperate

Figure 23: Contrite TFT Formalization in an Environment with Three Variants of Standing

In my source code I made one mistake in line 10 of the figure above. Instead of staying content and cooperating, I formalized CTFT so that it will become contrite and cooperate. Player thus decides for the correct action but gets a wrong standing. Yet the error has impact upon payoff that CTFT actor receives in a given round only in very specific circumstances. Since contrite TFT never defects while being content, there must be a mistaken implementation occurring and simultaneously the other player must defect in that specific round too so that we get into line 10 at all. Even then, however, we get different payoff only if in the next round opponent defected while the first player

[7] There are always 12 possible results of the last round encounter under this kind of standing formalization. It is because of 4 different outcomes and 3 different standing variants for each one of them.

cooperated, thus creating the possibility of not only different standing but also different action taken in the still next round. All this holds provided there are no other mistakes.

Obviously the chance that this bug in the source code would actually have some impact in form of decreased payoff for CTFT player is rather miniscule, not to speak about the possibility of significantly altering the results of full model simulations. In fact, if I would have to sum the effect of this bug in few words, it makes CTFT player willing to apologize for its own mistakes (and thus accept corresponding punishment) even if they did not cause any harm to opponent itself. Since generosity paid off in the full model, this kind of bug that enhanced forgiving could have made little harm to success of CTFT. Moreover, noting the fact that misconduct and misperception had basically the same effects upon success of strategies (see control simulations), and that CTFT overcomes only own mistakes of implementation, this bug seems not that grave with respect to general findings.

The last strategy that contained an error was REMORSE. This case is a bit more complicated. After trying to translate it into the form with three variants of standing so that we were able to disregard internal state of the opponent, one ultimately gets following twelve rules determining its action:

1.	After “CC” while content:	stay content and cooperate
2.	After “CC” while provoked:	become content and cooperate
3.	After “CC” while contrite:	become content and cooperate
4.	After “CD” while content:	become provoked and defect
5.	After “CD” while provoked:	stay provoked and defect
6.	After “CD” while contrite:	become content and defect
7.	After “DC” while content:	become contrite and cooperate
8.	After “DC” while provoked:	become content and defect
9.	After “DC” while contrite:	stay contrite and cooperate
10.	After “DD” while content:	stay content and cooperate
11.	After “DD” while provoked:	stay provoked and defect
12.	After “DD” while contrite:	stay contrite and cooperate

Figure 24: REMORSE Formalization in an Environment with Three Variants of Standing

The mistake was that instead of becoming content, REMORSE strategy in my source code retained its corresponding internal status (or standing) in line 2 as well as line 3. So if with respect to CTFT rule the error was limited to the single line, already two lines were affected in this case. And again as with the previous strategy, also here some specific circumstances must be met in order to cause this bug having any impact at all. As regards the second line on Figure 24, player using REMORSE has to make a mistake while provoked and the opponent must simultaneously cooperate, so that the required outcome arises at all. Even then the bug has any effect only if the other player does not defect (intentionally or not) at least until another occurrence of the first player's inaccurate implementation. Thus one needs at least two mistakes by the first player and no defection in between by the opponent in order to get any effect out of second line's bug. Overall impact of this line when compared to its repaired form is probably only slightly more defective behavior leading to only negligibly (if at all) higher payoffs than under properly formalized version, depending of course upon composition of the population itself.

Then as regards the third line that also had a bug on its own, one needs such an opponent that would be willing to defect after mutually cooperative outcome, in order to turn the effect of this error into reality. No mistake of implementation is necessary any more, but this is not very positive information, since it means higher probability of this bug having an impact upon overall results. Again, it depends on who interacts with whom, but as far as we take into account all possible circumstances, it seems that the repaired third line in REMORSE has slightly positive impact upon its performance even though it would have made it a little more defecting behavioral rule. Given the fact that error in line 2 had most likely an exactly reversed effect, I don't expect that the repaired version of REMORSE would have changed my results to any significant extent.

I fully realize that to be perfectly sure one would need to repeat the simulations *de novo*. Running the program again for several hundreds of times because of bugs in two moderately successful strategies is, however, far beyond the scientific criteria of a rigorous research I am willing to observe. The most important conclusion of the full model simulations dealt not with a problem of who won the reruns under what specific setting, but with the fact that power and distance had smaller influence upon results than expected. Neither this, nor the finding that generosity seems to pay off, would have been changed, if I rewrote the two above mentioned strategies and did everything all over again. Small errors present in the source code of CTFT and REMORSE would not have pushed them to the top of the list, if repaired. Not even control simulations with five most successful rules preselected in the full model would be influenced at the end.

8. Appendix B

Here follows a short description of individual strategies, used in my model:

[1] Tit-for-tat: it starts with cooperation and thereafter repeats opponent's last move. Strategy is nice, provocable, and forgiving. It won both of the Axelrod's tournaments.

[2] Champion: after ten unconditionally cooperative moves player using this strategy switch to tit-for-tat for another 15 moves and then defects only after other player's defection given the opponent has cooperated less then 60% of the time and the generated random number is bigger than adversary's rate of cooperation.

[3] Boerufsen: actor using this strategy starts with cooperation and then uses TFT as its basic strategy. However, after three consecutive mutual defections, it introduces unconditional cooperation. It also checks for echo effect and after three such consecutive moves it introduces single cooperation instead of the first next defection. Every 25 moves player tries to check if the other actor is either defector (in cooperated less than 3 times out of the last 25 interactions) or random player (it cooperated between 8 and 17 times, but less than 70% of that was after first player cooperation, i.e. it is unresponsive). If opponent seems to be either defector or random player, actor defects until the next check after 25 moves.

[4] Cave: actor using this strategy defects if the other player's defection frequency gets above 79, 65, or 39% of all their interactions and this after more than 19, 29, or 39 rounds respectively. Otherwise it always cooperates after other player's cooperation, and also after opponent's defection given that the opponent defected less than 18 times and that the random number between 0 and 1 is less than 0.5.

[5] Adams W.: actor using this strategy cooperates on the first two moves. Then, if the opponent defected less often than is the given threshold (4 initially), player cooperates. After reaching the threshold, player defects until opponent's next defection, in case of which it reduces the threshold by half, resets number of opponent's defections, and cooperates if random number between 0 and 1 is smaller than the new threshold.

[6] Graaskamp & Katzen: actor starts with cooperation and then repeats other player's last move. On the 11^{th}, 21^{st}, 31^{st}, 41^{st}, 51^{st} and 101^{st} encounter it checks, if score from previous interactions with the opponent is at most 7 points lower than the ideal score from uninterrupted cooperation. If this is not the case, player defects forever.

[7] Weiner: actor using this strategy plays TFT strategy unless there are more than 4 opponent's defections between penultimate and 13^{th} last encounter. In such a situation player defects irrespective of the opponent's last move. Also every time the opponent's defection three rounds ago is followed by cooperation in the penultimate round, actor updates its forgiveness factor by increasing it by 20 if the other player defected in the last move. If the forgiveness factor before updating was lower than the number of encounters so far, the player cooperates.

[8] Harrington: actor starts with cooperation. Unfortunately strategy is too complicated to be described here. See the source code for its decision-making process.

[9] Tideman & Chieruzzi: actor starts with cooperation and then repeats other player's last move. If the opponent starts defecting for the second, third, fourth time etc., then the first player introduces one, three, six etc. extra punishing defections, respectively,

required to reestablish cooperation. However, their mutual interactions is relaunched de novo if the other player fulfills four conditions: it hasn't just started new series of defections; the last relaunch was at least 10 moves ago; and total number of other player's defections differs from that of random strategy by at least 3 standard deviations of the population of possible numbers of defections of that random generator. Relaunch means that player cooperates immediately, but continues counting total number of defections. In the next move it behaves as if the game just started and it also resets number of times the other player switched from cooperation to defection.

[10] Kluepfel: it starts with cooperation and in the 2nd round defects with a probability of 60% only if the opponent defected in the first interaction. From the second round further on player counts number of opponent's cooperations and defections after the first player's cooperative or defective move. After 26th encounter, player introduces defection under two conditions: first, if number of opponent's cooperations after first player's defections is at least as big as half of the difference between number of first player's defections and three halves of square root of that number; and second, if number of opponent's defections after first player's cooperation is at least as big as half of the difference between number of first player's cooperations and three halves of square root of that number. In all other cases player repeats opponent's last move with a probability of 100%, 90%, 70%, and 60%, if the opponent did the same thing for the last three, two, or just one round (cooperation or defection) respectively.

[11] Getzler: in this case, defection of the other player has a one round half-life for the interacting partner, which is basically a forgetting function. Actor then defects only if the discounted sum of other player's defections is greater than a randomly generated number from 0 to 1.

[12] Leyvraz: it cooperates in the first encounter and thereafter makes choices according to previous 3 rounds. Player defects with a probability of 75% if the opponent defected in both of the last two rounds. It defects if the other player defected only in the penultimate encounter out of the last three moves, and it retaliates opponent's defection in the last encounter with a probability of 50% if the other player cooperated in the penultimate round and the round before that. In all other cases player cooperates.

[13] White: actor using this strategy cooperates in the first ten rounds and then it defects only after opponent's defection and even then only if the number of other player's defections multiplied by natural logarithm of the number of interactions is greater or at least equal to the very same number of interactions.

[14] Eatherley: actor using this strategy starts with cooperation and defects only after opponent's defection. Even then it defects only with a probability equal to the ratio of other player's defections over number of all moves.

[15] Black: strategy cooperates in the first 5 moves. Its memory is restricted to the last 5 encounters so the defection that occurred before that is forgotten. After 5 initial moves actor cooperates if the random number (from 0 to 1) multiplied by 25 is bigger than the number of defections raised to the second power and decreased by one.

[16] Richard Hufford: it starts with cooperation and TFT. As far as the other player did the same in the last move as the first player had done in the penultimate encounter, it continues with TFT, holds short-term sensibility parameter of the opponent at the highest level (initially 5), and increases long-term sensitivity by one on each encounter (initially same as number of encounters). If the long-term sensitivity gets above nine

tenths of the number of encounters and simultaneously short-term sensitivity is the highest possible i.e. 5, player cooperates. On the contrary, if the long-term sensitivity gets lower than five eights of the number of encounters or if short-term sensitivity gets below 3, actor defects. Furthermore, there is a given threshold RF (initially 20), when player defects for a single round after opponent cooperated for a consecutive RF-times. After this defection, player repeats opponent's last move, and then cooperates together with evaluating other player's response to introduced defection. If opponent retaliated, threshold is increased by 10. If it did not retaliated to introduced defection, threshold is gradually decreased to the integer part of the division of 20 by 2/3, 2/4, 2/5 etc.

[17] Yamachi: actor using this strategy decides according to the number in a particular cell of the 2x2 matrix. If the number is non-negative, player cooperates, otherwise it defects. Initially, numbers in all four cells are 0 and the game starts in an upper-left cell [0, 0]. If the opponent defected/cooperated on a previous round, number in a given cell is decreased/increased by one. Then the player moves to another or stays at a given cell based upon two rules: first, after opponents defection in round t-1, cell considered in round t+1 will be in a lower row of the 2x2 matrix; and second, if player decides in a given round to cooperate, in the following encounter it will decide according to number in the left cell of the selected row. After all that, if number of all encounters so far is greater than 40 and simultaneously the difference between cooperations and defections is less than one tenth of all moves, then the player chooses defection.

[18] Colbert: strategy cooperates on the first 8 moves except for the sixth one. From the 9^{th} interaction further on player cooperates until first defection of the other player. Then it defects twice followed by two unconditional cooperations. After that it starts cooperating again together with checking for defection on the previous round.

[19] Mauk: actor using this strategy plays TFT on the first 50 encounters and defects on the 51^{st} move. Then it plays TFT for another 5 interactions. According to opponent's behavior on these 5 moves player decides in 57^{th} round, which of the 4 available strategies to use for the rest of the game. If the other player seemed to use from 52^{nd} to 56^{th} interaction either TFT strategy (it defected on 52^{nd} and 54^{th} round) or the same strategy as the first player (it defected from 51^{st} to 54^{th} round), then actor again starts repeating opponent's last move. If opponent's gains from the first 56 interactions are not greater than 135, then the first player defects from 57^{th} encounter further on. Furthermore, if the other player defected from 51^{st} to 55^{th} only once and that on 53^{rd} encounter, then the first player consistently cooperates after 56^{th} round and from 118^{th} round further on plays TFT. Finally, under all other circumstances actor decides for a strategy that plays TFT but initiates defection on every 5^{th} to 15^{th} round (when next defection occurs is determined immediately after the last one).

[20] Mikkelson: actor using this strategy cooperates in the first two rounds. From the third encounter further on player decides according to special parameter, call it X, which is updated from the very first round. Initially, X is -3 and every round it is either decreased by 1 if opponent cooperated in the previous encounter, or increased by 2 if it defected. Now, from 3^{rd} round on player cooperates if X is less than 3. If not, and if number of encounters so far is less than 11, it defects and X gets value -1. Otherwise, i.e. if number of encounters is greater than 10, player cooperates if opponent defected on less than 15% of all encounters. Otherwise it defects.

[21] Rowsam: actor using this strategy makes decisions with help of two parameters (KAM and NPHA) updated every round and with initial value 0. If KAM is greater than

6, player defects. NPHA is decreased by 1 in a given round every time it gets above 0 in the previous one. Moreover, unless NPHA equals to 1 before this reduction, player cooperates. If none of those conditions is met, KAM is decreased by 1 every 18th encounter provided it is greater than 2. Given all that, player always cooperates except for every 6th encounter when it considers following decision-making rules. If the score gained from encounters with a given opponent so far is at least 2.5 times greater than (or equal to) the number of encounters multiplied by punishment payoff, then actor cooperates. Otherwise it defects and KAM is increased by 1. Furthermore, if score gained so far is less than 2x, 1.5x, or even less than 1.0x number of encounters multiplied by punishment payoff, then instead of KAM increased by 1, it is increased by 2, 3, or 5 points respectively (choice of defection is retained).

[22] Appold: actor using this strategy updates two key parameters every round. The first one represents ratio of opponent's defections that followed after first player's cooperation over overall number of first player cooperative moves (initially 1). The second one represents ratio of other player's defections after first actor's defections over total sum of first player's defections (initially 1). In the first four encounters player cooperates and also overlooks opponent's first defection afterwards. But thereafter it defects if the first player cooperated on the penultimate encounter and simultaneously the first parameter is greater than randomly generated number from <0, 1>, or if it defected on the penultimate encounter and simultaneously the second parameter is greater than randomly generated number.

[23] Grisell: actor using this strategy cooperates in a given move if number of other player's defections is less than half of the number of all their interactions.

[24] Tit-for-two-tats: player starts with cooperation and continues doing so until other player defects in two consecutive rounds. Cooperative behavior is restored immediately after opponent's cooperative move. John Maynard Smith submitted this strategy into the Axelrod's second tournament.

[25] Almy: it starts with cooperation and thereafter uses one of the four basic strategies: TF2T; TFT; Always defect; and exploiting strategy. When chosen, strategy is always played for 10 rounds, which is followed by an evaluation and possible shift, resetting of own and opponent's defections counts, and then another 10 moves. Exploitation strategy is selected if the opponent has never defected before the first considering of the exploitative strategy, or if it had been already selected before, if the first player didn't defect a once in the last 10 interactions (for detailed logic of exploitation see the source code). In special circumstances when selected newly selected rule's last performance is worse then that of the last used rule and there was at least one mutual defection in the last 10 encounters, then actor cooperates for 5 rounds and proceeds again to evaluation (exploitative rule being ruled out).

[26] Ambuehl & Hickey: actor using this strategy starts with cooperation, repeats opponent's last move on the next 4 rounds, and then cooperates if the other actor cooperated in majority of the last 5 encounters.

[27] Feathers: actor using this strategy starts with cooperation and counts number of other player's defections since its last cooperation (S) as well as overall number of its cooperations so far ©. If sum of gains from previous interactions with that particular opponent is at least ¾ of those from possible uninterrupted mutual cooperation given initial payoff matrix and if random number from 0 to 1 is not bigger than parameter P,

then the first player defects for one round and thereafter unconditionally cooperates for two. P equals to 0.95 increased by unit fraction of second power of number of encounters, decreased by sum of average payoffs after all previous cases of the two unconditional cooperations that followed after such defection increased by 5 and divided by 15, and decreased by 0.25 if opponent defected a round before. However, if the sum of gains so far is less than already mentioned ¾, then player defects unless two conditions if fulfilled. First, if overall sum of payoffs is even less than 7/12 of the possible gains from mutual cooperation, then the first player does the same as the opponent on the previous round. Second, if the random number from 0 to 1 is at most ¼ increased by share of C out of all encounters, by difference of first and second player's gains from their previous interactions with each other divided by 100, and by four unit fractions of number of interaction, plus decreased by ¼ of S, then the first player cooperates. This strategy is called Tranquilizer in Axelrod's second tournament.

[28] Grofman: actor using this strategy cooperates in the first two moves and uses TFT in the next five. From the eighth move on, actor cooperates only if it cooperated in the last round and the other player defected less than 3-times in the previous 7 encounters, or if the actor defected on the last round and the opponent defected at most once in previous 7 encounters. Otherwise player defects.

[29] Joss: actor using this strategy starts with cooperation and thereafter counts opponents cooperative moves and decides according to 5 different processes each assigned to different states (from 1 to 5; initial state is 1). In state 1 actor first defects with a probability of 10% together with changing status to 5, and if this defection does not occur, player proceeds in the same way as if it was playing according to state 5 except for the first step in state 5, which is to change status to 4. Based on the same steps of state 1 and 5, player first resets number of defections if opponent cooperated on the previous round, or alternatively increases number of defections. If this number exceeds 20 it cooperates, switches to state 3 and resets defections. In other cases (opponent cooperated or defections do not exceed 20), player inquires whether other player cooperated at least on 70% of round from the beginning up to the penultimate encounter (excluding). If it is so, actor repeats opponent's last move. If not, it shifts to state 2, defects, updates number of defections if the other player defected on the last move, and shifts to 3 if this number exceeds 10. Under state 2 player defects, updates number of defections and shifts to state 3 if it exceeds 10, or resets the number if opponent cooperated in the last interaction. Under state 3 actor does the same updating or resetting exercise with the exception that it is interested whether number of defection exceeds 20 instead of 10, and if it so, it cooperates and resets that number without changing the state. In other cases it repeats opponent's last move. Under state 4 the actor always cooperates. It shifts to state 1 if the opponent cooperated a round before, and otherwise increases generosity parameter by 1 (initially 0). When this parameter gets to 4, player resets number of defections and shifts to state 3. Otherwise player continues according to state 1 in the next round.

[30] Pinkley: this is Revised State Transition rule from Axelrod's second tournament. It cooperates on the first two encounters and thereafter analyzes other player's behavior through single-step Markov process updating the probability of the opponent's cooperation (on the last round) after all of the four possible end states (CC, CD, DC, DD on the penultimate encounter). Basically the higher is the number of previous interactions, the harder is it to profoundly shift the updated probabilities.

[31] Nydegger: it plays TFT for the first 3 moves unless it unilaterally cooperates in the first round and unilaterally defects in the second. In such a case it defects in the third move as well. After the third move it computes special defection score in which own previous defection has value of 2 points and that of the opponent 1 point. However, memory is only 3 rounds-long. Defection score from respective encounter is multiplied by 16, 4, and 1 from the oldest to the latest interaction respectively. Finally, actor cooperates if the defection score equals 0, 27-28, 32, 40-4, 46-8, 56-7, 59-60, or 62-63.

[32] Pebley: actor using this strategy repeats its previous move, if both players chose the same action in the last round. Otherwise it defects with a probability of 80%.

[33] Falk & Langsted: actor using this strategy starts with cooperation. Actor remembers outcomes of the last 8 rounds and counts how many times opponent cooperated/defected after first player's own cooperation or defection. If the other player defected for the last 8 rounds, actor gets to TFT mode and repeats opponent's last move from now on except for case when it perceives opponent as a random player. Then it defects for one round and resets defection parameter D. Opponent is considered random if values of its cooperation to defection ratios after first player's cooperation and defection are both between 3:2 and 1:2. Afterwards actor checks if it is in TFT mode. Next, if player's cooperation parameter C is positive, it cooperates and resets C to zero. As a next step actor evaluated if the opponent have just finished second consecutive cooperative move provided number of encounters is less than 30. If so actor cooperates. If not, it checks if opponent responded to the first player's single cooperation four rounds ago according to TFT logic. If yes, player cooperates and sets C to one. Further condition screened is that actor defects (together with resetting of D) if opponent defected at least by 3 rounds more frequently. Player resets D-parameter if any of the last five conditions evaluated is true except for the third one. It defects after any of them is fulfilled except for second and third and cooperates also if the fifth and thus the last condition if false. These conditions are (evaluated in the following order): whether the first player was the only one who defected round before; whether D-parameter is positive; whether both cooperated round before; whether the first player cooperated as the only one a round before; and whether it defected.

[34] Weiderman: actor using this strategy defects forever after three consecutive defective moves of the other player. Otherwise it cooperates.

[35] Adams R.: strategy starts with cooperation in the first two encounters. Thereafter actor retaliates after opponent's defection until opponent defects again. However, if opponent's first defection was on the first round, actor does not retaliate after 3rd, 6th, 9th defection etc. Similarly, if opponent's first defection was on the second round or later, player does not retaliate after that first defection, and then also after 4th, 7th, 10th etc. But even if according to the previously stated conditions actor decides not to retaliate after other player's defection, this decision can be still thwarted (for that single round) since there is only certain probability of the first player's cooperation after opponent's defection in the immediately previous interaction (initially 80%). This probability is, however, halved just after every defection of the opponent and again after all first actor's decisions taken immediately after other player's defection. It is halved as well after every second decision to defect that follows after opponent's cooperation in the previous move. Under all other possible circumstances actor cooperates.

[36] Dawes & Batell: actor using this strategy starts with cooperation and then cooperates after other player's cooperation in the previous round. If opponent defected a

round ago, then actor cooperates only if 5 is less than the product of 1.6667 raised to the power of overall sum of opponent's defections and 0.882 raised to the power of sum of cooperations. Otherwise it defects forever.

[37] Lefevre: actor using this strategy defects if the number of other player's defections is greater than one fifth of all their interactions. Otherwise it cooperates.

[38] Anderson: strategy starts with cooperation. After second encounter it begins counting how many times had the other player responded to cooperation (defection) with cooperation and how many times with defection. In the first 15 interactions player defects unless opponent cooperated in the previous encounter or unless number of other player's defection is greater than 2. From 16th encounter on player defects if the number of opponent's defections that followed after first player's cooperation is the same or greater than one third of the sum of all first players cooperations up to penultimate round. If this is not the case, actor chooses cooperation on all rounds except for every fourth, and even on every fourth one if the opponent defected only once out of the first 16 encounters and that precisely on the 16th one and without being provoked. If even this is not the case, player defects if there were not yet a single defection of the first player followed by opponent's retaliation, or if the sum of opponent's cooperations that followed after first player's defections is at least equal to integer value of one twelfth of all mutual encounters. In all other possible situations player cooperates.

[39] Downing: this strategy cooperates in the first two rounds and then decides according to the level of other player's responsiveness in the previous encounters. Every round actor updates ratio of opponent's cooperation after first player's own cooperation ('good') or alternatively after its defection ('bad'). Out of these two ratios actor computes two parameters: 'c' and 'alt' (c = 6 * good - 8 * bad - 2; alt = 4 * good - 5 * bad - 1). Then if 'c' is non-negative and simultaneously 'alt' is lower or equal to 'c', player cooperates. But if the first condition holds, while the second does not, then player does the opposite as in the last encounter. The same happens also in a different case that 'alt' is greater or equal to zero. All other situations cause defection. The same rule was submitted in the second tournament also by Stanley Quayle.

[40] Zimmerman: actor using this strategy starts with cooperation. Then if both players chose for the same option in the previous round, actor continues along the same path further on. However, in case of two players opting for different moves, first player counts how many times other actor unilaterally defected/cooperated. Nevertheless, it continues along the path set unless opponent's unilateral defections/cooperations reach certain threshold (4 and 8 respectively). Then the player resets the counts of unilateral moves, updates the thresholds, and switches to alternative move than it has pursued so far. If player cooperated up to that point, it updates the threshold for unilateral cooperation, which it will be counting immediately afterwards. Updating takes form of integer value of unilateral defections threshold increased by 1 and multiplied by 1.6667. If player defected in recent encounters, it updates value of unilateral defections threshold. New threshold will be the same as old one decreased by 3 and increased by integer value of score gained from previous encounters with a given opponent divided by product of punishment payoff and number of encounters.

[41] Newman: actor using this strategy cooperates on the first two moves and then updates probabilities (BETA and ALPHA) of opponent's cooperation on the last interaction after the first player's defection/cooperation in the penultimate one. In order to decide what to do player constructs two parameters. Parameter A, which is six times

ALPHA decreased by two and then further by nine times BETA, and parameter B, which is four times ALPHA decreased by one and then further by six times BETA. If A is nonnegative and simultaneously not lower than B, then player cooperates. If A is only nonnegative, then actor does the opposite as it did in the last encounter. It does the same if A is lower than zero and simultaneously B is nonnegative. However, actor counts cases when both A and B are negative, defects in the first three such situations, cooperates otherwise, and resets that number of cases (while choosing defection) if either of two interacting players cooperated in their previous encounter.

[42] Jones: this strategy starts with cooperation but for the logic of further decision-making see source code since strategy is too complicated for a written description.

[43] Shurmann: actor using this strategy starts with cooperation and then reciprocates opponent's cooperation provided it never defected in the past. If other player already defected at least once, actor decides its move according to special probability parameter (0.5 initially), which is updated on every encounter. If there was a mutual cooperation in the previous round, player cooperates with a probability equal to value of the last round parameter multiplied by 0.57 and increased by 0.43. In case of mutual defection in the previous encounter, player cooperates with a probability equal to value of the last round parameter multiplied by 0.74 and increased by 0.104. Finally, after either side's unilateral defection, player cooperates with a probability equal to value of the last round parameter multiplied by 0.5.

[44] Nussbacher: actor using this strategy cooperates on the first 10 moves. Then it counts opponent's defections in the last 10 encounters and decides whether to cooperate or not accordingly. If opponent defected 9 or 10 times out of last 10 moves, player defects with a probability of 94%. If the opponent defected 7, 6, 5, or 2-times, then player defects with a probability of 87%. In case of 4, 3, or 8 defections of the other player in the last 10 encounters, actor defects with a probability of 91,5%. If opponent defected only once, first player defects 23% of times. Finally if opponent consistently cooperated, player cooperates as well.

[45] Gladstein: actor using this strategy starts with defection. After opponent's first defection, player cooperates and from then on it uses TFT strategy. Between the first round and the opponent's first defection, actor defects if number of its own cooperations over other player's cooperations so far increased by one is greater or equal to one half. Thus it defects on the fourth, sixth, eighth encounter etc. This is the TESTER rule in the Axelrod's second tournament. It is also one of five 'representatives'.

[46] Batell: it defects forever after opponent's tenth defection. If this is not the case, it cooperates after opponent's cooperation in the last round. It does not retaliate defections unless they are separated by less than 3 cooperative moves. Then it defects forever.

[47] Smith D.: it cooperates with a probability of 0.95 on the first move, and also after other player's cooperation as well as after opponent's defection preceded by its cooperation. Player cooperates with a probability of 0.05 after 2, 3, 4, or 5 opponent's defections in a row. After 6^{th} defection of the other player in a row player clears its memory and thus tries cooperation with a probability of 0.95. However, if the opponent continues with uninterrupted defections, next attempt to cooperate is postponed. Player in fact cooperates with continuous defector after its 6^{th}, 14^{th}, 25^{th}, 39^{th} defections etc.

[48] Leyland: actor using this strategy starts with cooperation and each round updates overall number of opponent's defections as well as number of defections after the

opponent's last cooperation (I5). Parameter I5 is reset after the next cooperation of the other player unless this count of recent defections is less than 2. It is also reset after all first player's cooperations not based solely upon TFT decision-making, e.g. when actor repeats opponent's cooperation on the last round given I5 is higher than 5, which is always the very first condition evaluated in player's decision-making process after updating number of defections. In other situations actor plays TFT provided number of interactions so far is lower than 30. If number of encounters exceeds 29, player reconsiders cooperation probability (initially 75%) and lowers it by 20 points if opponent defected from 40 to 60% of all of their previous interactions. From 30th encounter further on actor usually repeats opponent's last move unless random number from 0 to 1 is higher than cooperation probability, when the actor defects. After every such a defection player acquires bad standing, which gets back to 'good' just after any non-TFT-based decision to cooperate, similarly as in case of the count of recent defections. After every defection caused solely by low cooperation probability actor repeats opponent's last move (if it does not defect again because of low probability of cooperation) and then, until good standing is restored again, it starts taking notice of the last opponent's move. If the other player cooperated, actor decreases cooperation probability by 5 points, changes it to zero if the result is negative, repeats opponent's last move if the result is at least 0.3, or if not the case proceeds again to generating random number and comparing it with cooperation probability. But if the other player defected, the first player cooperates, increases cooperation probability by 15 points, changes it to 1 if the result is bigger than one, and ensures that if I5 is now bigger than 5, it will cooperate in the next round (even before it could have updated cooperation probability) and will repeat that until I5 will not get below 6. Rules for resetting count of recent defection were already stated.

[49] McGurrin: actor using this strategy starts with defection and then cooperates for two rounds while paying attention to what the opponent was doing. If the opponent defected on both 1st and 2nd encounter, player shifts its strategy to TFT. If the other player cooperated in both interactions, the first player introduces defection every 8th round from now on and otherwise cooperates if the opponent cooperated on at least one of the preceding two rounds. If the other player cooperated on only one of the first two rounds, actor decides what to do according to opponent's move on the 3rd encounter. Given other player cooperated on the 3rd round, actor shifts its strategy to TF2T. Given opponent defected on the 3rd encounter, player shifts to TFT beginning with cooperation or defection according to what the other player did on the first round (cooperated or defected, respectively).

[50] Hollander: actor using this strategy defects only after two consecutive defections of the opponent. It also unilaterally introduces single defection every few rounds (with decreasing frequency).

[51] Grim trigger: player starts with cooperation and continues doing so until the first defection of the opponent. Thereafter it always defects. Strategy is totally unforgiving. This strategy was named FRIEDMAN in the first Axelrod tournament.

[52] George Hufford: actor using this strategy plays TFT on the first 5 encounters simultaneously saving number of defections in these moves. If previous 5 rounds were at least as profitable for the first player as the penultimate 5 encounters and the number of defections were less than 5, then actor introduces one more defection (out of every 5 moves) than before. However, if this decision brings lower gains to player than previous pattern of interactions, it switches back, reduces number of defections by one, and

continues doing so as long as it brings about at least as much gains out of the last 5 moves as was the case in the penultimate 5 encounters. On the other hand, if this condition is not fulfilled and actor again gets less profit from last 5 moves than from penultimate 5, player again starts step-by-step to introduce defections.

[53] Smoody: actor using this strategy defects only after other player's cooperation in previous round and even then only with 10% probability.

[54] Feld: strategy chooses its pattern of behavior every 20 moves. There are 5 basic patterns: always cooperate; cooperate even after defection with probability of 25%; play TFT; defect even after cooperation with a probability of 25%; and always defect. Actor plays TFT in the first 20 interactions and then gradually moves towards always defecting pattern. After reaching that pattern, it stays by that unless it brings about lower gains than the next more cooperative pattern (last 20 moves when it was using 25% probability to defect after opponent's cooperation). If that shift towards less defecting pattern of choices ensures higher profits (but not as high as that of even more cooperative pattern, because in that case player stays by present pattern of behavior), then player gradually moves after every 20 moves towards always cooperating end. Every change towards more cooperative pattern of behavior is accompanied by assumption that opponent cooperated in the very last round. After reaching always cooperating end, player stays by that unless it brings about lower profits than the last case of less cooperative pattern of behavior. In that case it moves again towards always defecting end, and employs similar conditions as when moving from more defecting end towards more cooperating one: it continues lowering cooperation probability as far as gains from the last case of interacting under that possible pattern is higher than those under present one. If not the case and simultaneously higher cooperation probability is not promising (lower gains prospect), player stays by the pattern it now employs instead of zipping back towards always cooperating end.

[55] Snodgrass: it first cooperates unconditionally for the 10 rounds, then it always defects for the next 10 interactions, and then alternate cooperation and defection for the following 10 encounters, plays TFT for another 10, and finally chooses TF2T for the fifth series of 10 rules. These five strategies are alternated each for 10 rounds unless some of them are deactivated in evaluation that occurs after 10th round played according to the last of the active strategies. Strategy is deactivated if it gained less than 90% of average gain per active strategy per 10 rounds in the last case that it was active. Strategy is reactivated if its average 10-round gain across all cases that it was active is bigger than the current average of active strategies per 10 rounds.

[56] Duisman: actor using this strategy cooperates on every odd interaction.

[57] Robertson: actor using this strategy starts with cooperation and repeats opponent's defection on the previous round if the number of interactions did not exceed 4 yet. After the fourth round player starts counting both overall number of other player's defections as well as number of consecutive defections since opponent's last cooperation. Player counts also opponent's consecutive cooperative moves. After opponent's cooperation, player cooperates unless number of opponent's defections is greater than the defection threshold (initially 20% of all interactions). However, even in that case it cooperates if number of other player's all defections is at least 20 times lower than the number of its consecutive cooperations multiplied by number of encounters. Furthermore, actor defects after opponent's cooperation also if the number of interactions up to that round is divisible by 12. This number is lowered by one every sixth defection induced in this

way. This process of defection initiation by way of probing divisibility of interaction's number is never tried again if the other player defects on the same round as in which the first player initiated defection in that way. Finally, after opponent's defection in the previous round, player cooperates (given number of interactions is greater than 4) unless overall number of opponent's defections is greater than the defection threshold or unless player defected for at least three consecutive interactions. From 20th interaction further on player decreases defection threshold to 10%.

[58] Rabbie: actor using this strategy cooperates on the first two moves and for the next 20 moves it defects unless index computed every round is greater than 2. This index is computed from the second round further on, and gets values of 4, 3, 2, and 1 if player made choices in two previous rounds in the following manner, respectively: it defected on both of these encounters; it defected on the penultimate round only; defected on the last one only; or didn't defected at all. From the third interaction player updates probabilities of other player's cooperation after 4 possible combinations of the first player's decisions in the last two rounds as indexed in an already stated way. From the second interaction actor also considers whether other player made the same choice on previous round or not. If the opponent consistently mirrors first player's choices, from 23rd encounter further on actor cooperates until the first time when both players chose for different option. After 22nd encounter and with interacting players using different strategies, player decides according to one of the 6 different strategies. What strategy player utilize depends upon expected gains that strategy will provide given different probabilities of opponent's cooperative behavior after 4 possible combinations of the first player's moves in the last 2 encounters, and given different weights attached to these probabilities within those 6 strategies. The most generous strategy always cooperates and the meanest one always defects. Decision-making process of weighting is slightly more favorable towards more defecting strategies.

[59] Hall: it cooperates on the first move, but on the second one only if opponent defected in the previous one. Thereafter it cooperates both after every odd cooperation of the other player as well as after every opponent's odd defection. Otherwise it defects.

[60] Friedland: it starts with cooperation and then computes probability of opponent's cooperation after first player's cooperation (Alpha) or defection (Beta). If the other player is viewed as playing according to random strategy, actor defects forever. Player is random if it did the same for three rounds at least once, if it didn't pick the same choice for more than 10 times, if it defected between 10 and 26 times (excluding) in the first 36 interactions, and if it changed the choice less than 26 times. If opponent is not seen as a random player, actor chooses the best of the following three strategies given Alpha and Beta: always cooperate; always defect; alternate cooperation and defection.

[61] Random: player randomly chooses between cooperation and defection.

[62] Hotz: actor using this strategy cooperates with probability of 0.1 in the first 100 interactions, with probability of 0.05 in the second hundred, with that of 0.15 in the third hundred, and always defects from 300th move on.

[63] Win-stay-lose-shift: it starts with cooperation. Thereafter it defects only if the two players opted for different alternatives in the previous round. Otherwise it cooperates.

[64] Suspicious tit-for-tat strategy: player starts with defection and then repeats the other player's last move.

[65] Generous tit-for-tat: player starts with cooperation and then repeats the other player's last move with a certain probability to generously disregard defection and cooperate further. Optimal generosity level equation determines actual extent of generosity. Optimal level is equal to the lower of the following two values: (R - P)/(T - P) and (2R - S - T)/(R - S)].

[66] Contrite tit-for-tat: while determining how to move in a given round player considers not only history of previous interactions but also standing of both players. Player receives good standing whenever it cooperates, but also if it defects given its previous round standing was good while opponent's standing was bad. Otherwise it gets bad standing. Player using CTFT strategy starts with cooperation and does so always except in case when in the previous round it was in good standing while the other player was in bad. In case of three possible standings (content, provoked, contrite) instead of only two (good, bad), one can formulate CTFT strategy even without need to consider other player's standing.

[67] Remorse: while determining how to move in a given round it considers not only history of previous interactions but also the standing of both players. Player receives good standing whenever it cooperates, but also if it defects given its previous round standing was good while opponent's standing was bad. Otherwise it gets bad standing. Player using Remorse strategy starts with cooperation and then does the same only if both players cooperated in the previous round or if it is in bad standing. In case of three possible standings (content, provoked, contrite) instead of only two (good, bad), one can formulate Remorse strategy even without need to consider other player's standing.

[68] Walt: player employing this strategy makes use of the following two variables - probability of interaction occurrence, and cooperativeness of the opponent (ratio of mutually cooperative outcomes to all their interactions). First, if the probability of interaction is greater than 2/3 and opponent's cooperativeness is lower or equal to one half, then WALT always defects (DEF) except after opponent's cooperation given randomly generated number from 0 to 1 is simultaneously lower than the level of cooperativeness. If this cooperativeness falls between 0.51 and 0.76, actor plays TFT, and if it is greater than or equal to 0.76, player always cooperates (COOP) except after opponent's defection given randomly generated number from 0 to 1 is simultaneously greater than the mentioned cooperativeness level. Second, if probability of interaction is greater than 1/3 but lower than 2/3, then actor using WALT strategy plays DEF, TFT, and COOP given level of cooperativeness corresponding to <26, 26-75, and >75 respectively. Finally, if the probability of interaction is lower than 1/3, player always cooperates (COOP) given cooperativeness reaching more than 50%, always defects (DEF) if it stays under 26%, and plays TFT under remaining circumstances.

[69] Balance: the greater is the power of opponent, the less cooperative is this strategy. To be more specific, player computes ratio of opponent's power to the average capability level in the system, which normalized to the interval from 0 to 1 helps determine the next step. If this ratio falls between 0.26 and 0.76, actor plays TFT. If it is less than 0.26, player always cooperates except after opponent's defection given randomly generated number from 0 to 1 is simultaneously lower than the mentioned ratio. If it is greater than or equal to 0.76, player always defects except after opponent's cooperation given randomly generated number from 0 to 1 is simultaneously greater than the mentioned ratio.

[70] Bandwagon: the greater is the power of opponent, the more cooperative is this strategy. To be more specific, player computes ratio of opponent's power to the average capability level in the system, which normalized to the interval from 0 to 1 helps determine the next step. If this ratio falls between 0.26 and 0.76, actor plays TFT. If it is less than 0.26, player always defects except after opponent's cooperation given randomly generated number from 0 to 1 is simultaneously lower than the mentioned ratio. If it is greater than or equal to 0.76, player always cooperates except after opponent's defection given randomly generated number from 0 to 1 is simultaneously greater than the mentioned ratio.

[71] Weakling: while determining how to move in a given round player considers not only history of previous interactions but also the standing of both players. Player receives good standing whenever it cooperates, but also if it defects given its previous round standing was good while opponent's standing was bad. Otherwise it gets bad standing. Player using Weakling strategy starts with cooperation and then does the same only if it is in bad standing. In case of three possible standings (content, provoked, contrite) instead of only two (good, bad), one can formulate Weakling strategy even without need to consider other player's standing.

[72] Grofman 1st: actor using this strategy cooperates on the first round and thereafter does the same unless they chose with the opponent different moves in the previous encounter and the randomly generated number from 0 to 1 is greater than 2 / 7.

[73] Feld 1st: it starts with TFT strategy but gradually lowers the probability of cooperation after opponent's cooperation in the previous round so that by the 200th interaction the probability is 0.5. After 200th encounter the probability stops decreasing.

[74] Joss 1st: strategy from the Axelrod's first tournament. Actor begins with cooperation and then repeats other player's cooperative move in the previous round with the 90% probability. It always defects after opponent's defection in the previous round.

[75] Davis: this strategy from the Axelrod's first tournament cooperates in the first ten interactions and then defects forever after opponent's single defection.

[76] Shubik: actor using this strategy starts with cooperation and then counts the number of opponent's unilateral defections. After every such a defection player defects so many times as is the number of opponent's unilateral defections so far. Then it tries to reestablish cooperation.

[77] Tullock: player using this strategy cooperates in the first 11 interactions and then returns by 10% less cooperative moves than the opponent did on the previous 10 moves.

[78] All-defection: player always defects.

[79] All-cooperation: player always cooperates.

[80] Vienna: strategy was used in papers by Martin Nowak and Karl Sigmund from the University of Vienna. Actor is defined by random combination of four numbers each from the interval (0,1) that determine the probability of its cooperation after four possible outcomes of the Prisoner's Dilemma in the previous round, i.e. CC, CD, DC, and DD. If included in the pool, this strategy is assigned to all remaining players after other selected rules have been allocated exactly once.

9. List of Figures

10. References

Abell, Peter. (1992). Is rational choice theory a rational choice of theory? IN: Coleman, J. S. – Fararo, T. J. (eds.): *Rational choice: Advocacy and critique*. Newbury Park: Sage Publications, pp. 183-206.

Albert, Mathias – Cederman, Lars-Eric (2010): Introduction: Systems Theorizing in IR. In: Albert, Mathias – Cederman, Lars-Eric – Wendt, Alexander (eds.): *New Systems Theories of World Politics*. Houndmills: Palgrave Macmillan, pp. 1-20.

Angell, Norman (1913): *The Great Illusion*. London: Heinemann.

Ashlock, Dan – Smucker, Mark D. – Stanley, E. Ann – Tesfatsion, Leigh (1996): Preferential Partner Selection in an Evolutionary study of Prisoner's Dilemma. *BioSystems*, Vol. 37, No. 1-2, pp. 99-125.

Axelrod, Robert (1980a): Effective Choice in the Prisoner's Dilemma. *Journal of Conflict Resolution*, Vol. 24, No. 1, pp. 3-25.

Axelrod, Robert (1980b): More Effective Choice in the Prisoner's Dilemma. *Journal of Conflict Resolution*, Vol. 24, No. 3, pp. 379-403.

Axelrod, Robert (1981): The Emergence of Cooperation among Egoists. *American Political Science Review*, Vol. 75, No. 2, pp. 306-318.

Axelrod, Robert (1990 [1984]): *The Evolution of Cooperation.* Harmondsworth: Penguin Books.

Axelrod, Robert (1997): *The Complexity of Cooperation.* Princeton: Princeton University Press.

Axelrod, Robert (2003): Advancing the Art of Simulation in the Social Sciences. *Japanese Journal for Management Information System*, Vol. 12, No. 3, pp. 3-16.

Axelrod, Robert (2006): Agent-based modeling as a bridge between disciplines. IN: Tesfatsion, Leigh – Judd, Kenneth J. (eds.): *Handbook of Computational Economics: Agent-Based Computational Economics, Vol. 2.* Amsterdam & Oxford: North-Holland, pp. 1565-84.

Axelrod, Robert – Dion, Douglas (1988): The Further Evolution of Cooperation. *Science,* Vol. 242, No. 4884, pp. 1385-1390.

Axtell, Robert – Axelrod, Robert – Epstein, Joshua – Cohen, Michael D. (1996): Aligning Simulation Models: A Case Study and Results. *Computational and Mathematical Organization Theory*, Vol. 1, No. 2, pp. 123–41.

Barabási, Albert-László – Albert, Réka (1999): Emergence of Scaling in Random Networks. *Science*, Vol. 286, No. 5439, pp. 509-512.

Batali, John – Kitcher, Philip (1995): Evolution of Altruism in Optional and Compulsory Games. *Journal of Theoretical Biology*, Vol. 175, No. 2, pp. 161-171.

Behr, Roy L. (1981): Nice Guys Finish Last – Sometimes. *Journal of Conflict Resolution,* Vol. 25, No. 2, pp. 289-300.

Bendor, Jonathan (1987): In Good Times and Bad: Reciprocity in and Uncertain World. *American Journal of Political Science*, Vol. 31, No. 3, pp. 531-558.

Bendor, Jonathan (1993): Uncertainty and the Evolution of Cooperation. *Journal of Conflict Resolution*, Vol. 37, No. 4, pp. 709-734.

Bendor, Jonathan – Kramer, Roderick M. – Stout, Suzanne (1991): When in Doubt… Cooperation in a Noisy Prisoner's Dilemma. *Journal of Conflict Resolution,* Vol. 35, No. 4, pp. 691-719.

Bendor, Jonathan – Kramer, Roderick – Swistak, Piotr (1996): Cooperation Under Uncertainty: What is New, What is True, and What is Important. *American Sociological Review,* Vol. 61, No. 2, pp. 333-338.

Bendor, Jonathan – Swistak, Piotr (1995): Types of evolutionary stability and the problem of cooperation. *Proceedings of the National Academy of Sciences of the United States of America,* Vol. 92, No. 8, pp. 3596-3600.

Bendor, Jonathan – Swistak, Piotr (1997): The Evolutionary Stability of Cooperation. *American Political Science Review,* Vol. 91, No. 2, pp. 290-307.

Bennett, Andrew – Elman, Colin (2007): Case Study Methods in the International Relations Subfield. *Comparative Political Studies,* Vol. 40, No. 2, pp. 170-195.

Bhavnani, Ravi – Miodownik, Dan (2009): Ethnic Polarization, Ethnic Salience, and Civil War. *Journal of Conflict Resolution,* Vol. 53, No. 1, pp. 30-49.

Billard, Edward A. (1996): Evolutionary strategies of stochastic learning automata in the prisoner's dilemma. *BioSystems,* Vol. 39, No. 2, pp. 93-107.

Boulding, Kenneth E. (1962): *Conflict and Defense: A General Theory*. New York: Harper & Row Publishers.

Brauchli, Kurt – Killingback, Timothy – Doebeli, Michael (1999): Evolution of Cooperation in Spatially Structured Populations. *Journal of Theoretical Biology,* Vol. 200, pp. 405-417.

Boerlijst, Maarten C. – Nowak, Martin A. – Sigmund, Karl (1997): The Logic of Contrition. *Journal of Theoretical Biology,* Vol. 185, No. 3, pp. 281-293.

Bourdieu, Pierre (1999 [1984]): *Distinction: A Social Critique of the Judgment of Taste*. London: Routledge and Kegan Paul.

Boyd, Robert (1989): Mistakes Allow Evolutionary Stability in the Repeated Prisoner's Dilemma Game. *Journal of Theoretical Biology,* Vol. 136, No. 1, pp. 47-56.

Boyd, Robert – Lorberbaum, Jeffrey P. (1987): No Pure Strategy is Evolutionarily Stable in the Repeated Prisoner's Dilemma Game. *Nature*, Vol. 327, No. 6117, pp. 58-59.

Bremer, Stuart A. – Mihalka, Michael (1977): *Machiavelli in Machina: Or Politics among Hexagons.* IN: Deutsch, Karl W. – Fritsch, Bruno – Jaguaribe, Helio – Markovits, Andei S. (eds.): *Problems of World Modeling.* Cambridge: Ballinger, pp. 303-337.

Bueno de Mesquita, Bruce – Lalman, David (1992): *War and Reason: Domestic and International Imperatives*. New Haven: Yale University Press.

Busch, Marc L. – Reinhardt, Eric R. (1993): Nice Strategies in a World of Relative Gains: The Problem of Cooperation under Anarchy. *Journal of Conflict Resolution,* Vol. 37, No. 3, pp. 427-445.

Cederman, Lars-Erik (2001): Modeling the Democratic Peace as a Kantian Selection Process. *Journal of Conflict Resolution,* Vol. 45, No. 4, pp. 470-502.

Cederman, Lars-Erik (2005): Computational Models of Social Forms: Advancing Generative Process Theory. *American Journal of Sociology,* Vol. 110, No. 4, pp. 864–893.

Cohen, Michael D. – Riolo, Rick L. – Axelrod, Robert (2001): The role of social structure in the maintenance of cooperative regimes. *Rationality and Society,* Vol. 13, No. 1, pp. 5-32.

Cusack, T.R. – Stoll, R.J. (1990): *Exploring Realpolitik: Probing International Relations Theory with Computer Simulation.* Boulder: Lynne Rienner.

Davis, Christina (2009): Linkage Diplomacy: Economic and Security Bargaining in the Anglo-Japanese Alliance, 1902-23. *International Security*, Vol. 33, No. 3, pp. 143-79.

Deutsch, Karl et al. (1969 [1957]): *Political Community and the North Atlantic Area*. New York: Greenwood Press.

Deutsch, Morton (1958): Trust and Suspicion. *Journal of Conflict Resolution,* Vol. 2, No. 4, pp. 265-279.

Dibble, Catherine (2006): Computational Laboratories for Spatial Agent-Based Models. IN: Tesfatsion, Leigh – Judd, Kenneth J. (eds.): *Handbook of Computational Economics: Agent-Based Computational Economics, Vol. 2.* Amsterdam & Oxford: North-Holland, pp. 1511-1548.

Doebeli, Michael – Hauert, Christoph (2005): Models of cooperation based on the Prisoner's Dilemma and the Snowdrift game. *Ecology Letters,* Vol. 8, No. 7, pp. 748-766.

Downs, George W. – Rocke, David M. – Siverson, Randolph M. (1986): Arms Races and Cooperation. IN: Oye, Kenneth A. (ed.): *Cooperation under Anarchy*. Princeton: Princeton University Press, pp. 118-146.

Duffy, Gavan – Frederking, Brian (2009): Changing the Rules: A Speech Act Analysis of the End of the Cold War. *International Studies Quarterly*, Vol. 53, No. 2, pp. 325-47.

Epstein, Joshua M. (1999): Agent-Based Computational Models and Generative Social Science. *Complexity*, Vol. 4, No. 5, pp. 41-60.

Epstein, Joshua M. (2002): Modeling civil violence: An agent-based computational approach. *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 99, Supplement 3, pp. 7243-7250.

Epstein, Joshua M. – Axtell, Robert (1996): *Growing Artificial Societies: Social Science from the Bottom Up*. Washington: Brookings Institution Press

Eshel, Ilan – Herreiner, Dorothea K. – Samuelson, Larry – Sansone, Emilia – Shaked, Avner (2000): Cooperation, Mimesis, and Local Interaction. *Sociological methods Research*, Vol. 28, No. 3, pp. 341-364.

Farrell, Joseph – Ware, Roger (1989): Evolutionary Stability in the Repeated Prisoner's Dilemma. *Theoretical Population Biology*, Vol. 36, No. 2, pp. 161-166.

Fearon, D. James (1998): Domestic Politics, Foreign Policy, and Theories of International Relations. *American Review of Political Science*, Vol. 1, pp. 289-313.

Fearon, D. James – Wendt, Alexander (2002): *Rationalism versus Constructivism: A Skeptical View*. IN: Carlsnaes, Walter – Risse, Thomas – Simmons, Beth (eds.) *Handbook of International Relations*. New York: Sage, pp. 52-72.

Feaver, Peter D. – Hellman, Gunther – Schweller, Randall L. – Taliaferro, Jeffrey W. – Wohlforth, William C. – Legro, Jeffrey W. – Moravcsik, Andrew (2000): Brother, Can You Spare a Paradigm? (Or Was Anybody Ever a Realist?) *International Security*, Vol. 25, No. 1, pp. 165-193.

Fehr, Ernst – Fischbacher, Urs (2003): The nature of human altruism. *Nature*, Vol. 425, No. 6960, pp. 785-791.

Frean, Marcus R. (1994): The prisoner's dilemma without synchrony. *Proceedings of the Royal Society B: Biological Sciences*, Vol. 257, No. 1348, pp. 75-79.

Friedrichs, Jörg – Kratochwil, Friedrich (2009): On Acting and Knowing: How Pragmatism Can Advance International Relations Research and Methodology. *International Organization*, Vol. 63, No. 4, pp. 701-31.

Fudenberg, Drew – Maskin, Eric (1986): The Folk Theorem in Repeated Games with Discounting or with Incomplete Information. *Econometrica*, Vol. 54, No. 3, pp. 533-554.

Fudenberg, Drew – Maskin, Eric (1990): Evolution and Cooperation in Noisy Repeated Games. *American Economic Review,* Vol. 80, No. 2, pp. 274-279.

Galtung, Johan (1968): Small Group Theory and the Theory of International Relations. IN: Kaplan, Morton A. (ed.): *New Approaches to International Relations.* New York: St. Martin's Press, pp. 270-302.

Gilbert, Nigel (1995): *Emergence in social simulation.* IN: Gilbert, Nigel – Conte, Rosaria (eds.): *Artificial Societites: The Computer Simulation of Social Life.* London: UCL Press, pp. 122-131.

Gilbert, Nigel – Terna, Pietro (2000): How to Build and Use Agent-Based Models in Social Science. *Mind & Society*, Vol. 1, No. 1, pp. 57-72.

Gilbert, Nigel – Troitzsch, Klaus G. (2005): *Simulation for the Social Scientist.* Maidenhead: Open University Press.

Gilpin, Robert (2002 [1981]): *War and Change in World Politics.* Cambridge: Cambridge University Press.

Gotts, Nicholas M. – Polhill, J. Gareth – Law, Alistair N. R. (2003): Agent-Based Simulation in the Study of Social Dilemmas. *Artificial Intelligence Review*, Vol. 19, No. 1, pp. 3-92

Grieco, Joseph M. (1988): Anarchy and the Limits of Cooperation: A Realist Critique of the Newest Liberal Institutionalism. *International Organization*, Vol. 42, No. 3, pp. 485-507.

Grim, Patrick (1995): The Greater Generosity of the Spatialized Prisoner's Dilemma. *Journal of Theoretical Biology*, Vol. 173, No. 4, pp. 353-359.

Halas, Matus (2009): Post Scriptum on Relative and Absolute Gains. *Perspectives: Review of International Affairs*, Vol. 17, No. 1, pp. 27-55.

Hamman, Henry L. (1998): *Remodeling International Relations: New Tools from New Science?* IN: Kubalkova, Vendulka – Onuf, Nicholas – Kowert, Paul (eds.): *International Relations in a Constructed World.* New York: M.E. Sharpe, pp. 173-192.

Harman, Gilbert H. (1965): The Inference to the Best Explanation. *The Philosophical Review*, Vol. 74, No. 1, pp. 88-95.

Hayashi, Nahoko – Yamagishi, Toshio (1998): Selective Play: Choosing Partners in an Uncertain World. *Personality and Social Psychology Review*, Vol. 2, No. 4, pp. 276-289.

Hobbes, Thomas (1998 [1651]): *Leviathan.* Oxford: Oxford University Press.

Hofbauer, Josef – Sigmund, Karl (1998): *Evolutionary Games and Population Dynamics.* Cambridge: Cambridge University Press.

Hoffmann, Michael (1999): Problems with Peirce's Concept of Abduction. *Foundations of Science*, Vol. 4, No. 3, pp. 271-305.

Hoffmann, Robert (1999): The independent localisations of interaction and learning in the repeated Prisoner's Dilemma. *Theory and Decision,* Vol. 47, No. 1, pp. 57-72.

Hoffmann, Robert (2000): Twenty Years on: The Evolution of Cooperation Revisited. *Journal of Artificial Societies and Social Simulation,* Vol. 3, No. 2.

Hollis, Martin – Smith, Steve (1991): *Explaining and Understanding International Relations*. Oxford: Clarendon Press.

Hopf, Ted (1998): The Promise of Constructivism in International Relations Theory. *International Security,* Vol. 23, No. 1, pp. 171-200.

Ifti, Margarita – Killingback, Timothy – Doebeli, Michael (2004): Effects of neighbourhood size and connectivity on the spatial Continuous Prisoner's Dilemma. *Journal of Theoretical Biology*, Vol. 231, No. 1, pp. 97-106.

Jackson, Patrick T. – Nexon, Daniel H. (2009): Paradigmatic Faults in International-Relations Theory. *International Studies Quarterly,* Vol. 53, No. 4, pp. 907-930.

Jepperson, Ronald L. – Wendt, Alexander – Katzenstein, Peter J. (1996): Norms, Identity, and Culture in National Security. IN: Katzenstein, Peter J. (ed.): *The Culture of National Security: Norms and Identity in World Politics.* New York: Columbia University Press, pp. 33-75.

Jervis, Robert (1976): *Perception and Misperception in International Politics.* Princeton: Princeton University Press.

Jervis, Robert (1982): Security Regimes. *International Organizations*, Vol. 36, No. 2, pp. 357-378.

Jervis, Robert (1986): From Balance to Concert: A Study of International Security Cooperation. IN: Oye, Kenneth A. (ed.): *Cooperation Under Anarchy*. Princeton: Princeton University Press, pp. 58-79.

Jervis, Robert (1997): *System Effects: Complexity in Political and Social Life.* Princeton: Princeton University Press.

Johnson, Paul E. (1999): Simulation Modeling in Political Science. *American Behavioral Science,* Vol. 42, No. 10, pp. 1509-1530.

Josephson, John R. – Josephson, Susan G. (eds. 1996): *Abductive Inference.* Cambridge: Cambridge University Press.

Jupille, Joseph – Caporaso, James A. – Checkel, Jeffrey T. (2003): Integrating Institutions: Rationalism, Constructivism and the Study of the European Union. *Comparative Political Studies,* Vol. 36, No. 1-2, pp. 7–40.

Kapitan, Tomis (1992): Peirce and the Autonomy of Abductive Reasoning. *Erkenntnis,* Vol. 37, No. 1, pp. 1-26.

Kaplan, Morton A. (1962): *System and Process in International Politics*. New York: John Wiley & Sons.

Karásek, Tomáš (2007): Integrace nebo mocenská rovnováha? Konceptualizace „vysoké" a „nízké" zahraničně-bezpečnostní politiky v rámci Evropské unie. *Mezinárodní vztahy*, Vol. 42, No. 2, pp. 5-30.

Kavalski, Emilian (2007): The fifth debate and the emergence of complex international relations theory: notes on the application of complexity theory to the study of international life. *Cambridge Review of International Affairs*, Vol. 20, No. 3, pp. 435-454.

Keohane, Robert O. (1984): *After Hegemony*. Princeton: Princeton University Press.

Keohane, Robert O. (1986): Reciprocity in international relations. *International Organization,* Vol. 40, No. 1, pp. 1-27.

Keohane, Robert O. (1988): International Institutions: Two Approaches. *International Studies Quarterly,* Vol. 32, No. 4, pp. 379-396.

Killingback, Timothy – Doebeli, Michael (2002): The Continuous Prisoner's Dilemma and the Evolution of Cooperation through Reciprocal Altruism with Variable Investment. *American Naturalist,* Vol. 160, No. 4, pp. 421-438.

Killingback, Timothy – Doebeli, Michael – Knowlton, Nancy (1999): Variable investment, the Continuous Prisoner's Dilemma, and the origin of cooperation. *Proceedings of the Royal Society B: Biological Sciences,* Vol. 266, No. 1430, pp. 1723-1728.

King, Gary – Keohane, Robert O. – Verba, Sidney (1994): *Designing Social Inquiry*. Princeton: Princeton University Press.

Knutsen, Torbjørn (1997): *A History of International Relations Theory*. Manchester: Manchester University Press.

Kraines, David – Kraines, Vivian (1989): Pavlov and the Prisoner´s Dilemma. *Theory and Decision,* Vol. 26, No. 1, pp. 47-79.

Kreps, David M. – Milgrom, Paul – Roberts, John – Wilson, Robert (1982): Rational Cooperation in the Finitely Repeated Prisoner's Dilemma. *Journal of Economic Theory,* Vol. 27, No. 2, pp. 245-252.

Le, Stephen – Boyd, Robert (2007): Evolutionary Dynamics of the Continuous Iterated Prisoner's Dilemma. *Journal of Theoretical Biology,* Vol. 245, No. 2, pp. 258-267.

Legro, Jeffrey W. – Moravcsik, Andrew (1999): Is Anybody Still a Realist? *International Security,* Vol. 24, No. 2, pp. 5-55.

Lindgren, Kristian – Nordahl, Mats G. (1994): Evolutionary Dynamics of Spatial Games. *Physica D*, Vol. 75, No. 1-3, pp. 292-309.

Lipton, Peter (2004): *Inference to the Best Explanation.* 2nd edition, Abingdon: Routledge.

Lorberbaum, Jeffrey (1994): No Strategy is Evolutionary Stable in the Repeated Prisoner's Dilemma. *Journal of Theoretical Biology,* Vol. 168, No. 2, pp. 117-130.

Macy, Michael W. – Willer, Robb (2002): From Factors to Actors: Computational Sociology and Agent-Based Modeling. *Annual Review of Sociology,* Vol. 28, pp. 143–66.

Masuda, Naoki – Aihara, Kazuyuki (2003): Spatial prisoner's dilemma optimally played in small-world networks. *Physics Letters A,* Vol. 313, No. 1-2, pp. 55-61.

May, Robert M. (1987): More Evolution of Cooperation. *Nature*, Vol. 327, No. 6117, pp. 15-17.

Maynard Smith, John – Price, George R. (1973): The Logic of Animal Conflict. *Nature,* Vol. 246, No. 5427, pp. 15-18.

Mearsheimer, John J. (2003): *The Tragedy of Great Power Politics*. New York: W. W. Norton & Company.

Molander, Per (1985): The Optimal Level of Generosity in a Selfish, Uncertain Environment. *Journal of Conflict resolution,* Vol. 29, No. 4, pp. 611-618.

Morgenthau, Hans J. (1993 [1948]): *Politics Among Nations: The Struggle for Power and Peace.* Boston: McGraw-Hill.

Morrow, James D. (1994): *Game Theory for Political Scientists.* Princeton: Princeton University Press.

Mueller, Ulrich (1987): Optimal Retaliation for Optimal Cooperation. *Journal of Conflict Resolution,* Vol. 31, No. 4, pp. 692-724.

Nicholson, Michael (1992): *Rationality and the Analysis of International Conflict.* Cambridge: Cambridge University Press.

Nowak, Martin A. (2006): Five Rules for the Evolution of Cooperation. *Science,* Vol. 314, No. 5805, pp. 1560-1563.

Nowak, Martin A. – May, Robert M. (1992): Evolutionary Games and Spatial Chaos. *Nature,* Vol. 359, No. 6398, pp. 826-829.

Nowak, Martin A. – Sigmund, Karl (1992): Tit for tat in heterogeneous populations. *Nature,* Vol. 355, No. 6357, pp. 250-253.

Nowak, Martin A. – Sigmund, Karl (1993): A strategy of win-stay, lose-shift that outperforms tit-for-tat in the Prisoner's Dilemma game. *Nature*, Vol. 364, No. 6432, pp. 56-58.

Nowak, Martin A. – Sigmund, Karl (1994): The Alternating Prisoner's Dilemma. *Journal of Theoretical Biology*, Vol. 168, No. 2, pp. 219-226.

Ó Tuathail, Gearóid (1996): *Critical Geopolitics*. Minneapolis: University of Minnesota Press.

Olson, Mancur (1971 [1965]): *The Logic of Collective Action.* Cambridge: Harvard University Press.

Onuf, Nicholas (1998): *Constructivism: A User's Manual*. IN: Kubalkova, Vendulka – Onuf, Nicholas – Kowert, Paul (eds.): *International Relations in a Constructed World.* New York: M.E. Sharpe, pp. 58-78

Ordeshook, Peter C. (1986) *Game Theory and Political Theory: An Introduction.* Cambridge: Cambridge University Press.

Oye, Kenneth A. (1985): Explaining Cooperation Under Anarchy: Hypotheses and Strategies. *World Politics*, Vol. 38, No. 1, pp. 1-24.

Parunak, H. van Dyke – Savit, Robert – Riolo, Rick L. (1998): Agent-Based Modeling vs. Equation-Based Modeling: A Case Study and Users' Guide. IN: Sichman, J. S. et al (eds.): *Proceedings of Multi-Agent Systems and Agent-Based Simulation*. Berlin: Springer Verlag, pp. 10-25.

Peirce, Charles S. (1994): *The Collected Papers of Charles Sanders Peirce*. Edited electronic version by John Deely reproducing Hartshorne, Charles – Weiss, Paul (eds. 1931-1935): Vols. I-VI; and Burks, Arthur W. (ed. 1958): Vols. VII-VIII. Cambridge: Harvard University Press.

Pelc, Andrzej – Pelc, Krzysztof J. (2009): Same Game, New Tricks: What Makes a Good Strategy in the Prisoner's Dilemma? *Journal of Conflict Resolution*, Vol. 53, No. 5, pp. 774-793.

Pepinsky, Thomas B. (2005): From Agents to Outcomes: Simulation in International Relations. *European Journal of International Relations*, Vol. 11, No. 3, pp. 367-394.

Pierson, Paul (2000): Path Dependence, Increasing Returns, and the Study of Politics. *American Political Science Review*, Vol. 94, No. 2, pp. 251-267.

Polhill, J. Gary – Izquierdo, Luis R. – Gotts, Nicholas M. (2006): What every agent-based modeller should know about floating point arithmetic. *Environmental Modelling & Software*, Vol. 21, No. , pp. 283-309.

Popper, Karl R. (2002 [1959]): *Logic of Scientific Discovery.* London: Routledge.

Railsback, Steven F. – Lytinen, Steven L. – Jackson, Stephen K. (2006): Agent-based Simulation Platforms: Review and Development Recommendations. *Simulation,* Vol. 82, No. 9, pp. 609-623.

Rapoport, Anatol – Chammah, Albert M. (1965): *Prisoner's Dilemma.* Ann Arbor: The University of Michigan Press.

Rasmussen, Eric (1989) *Games and Information: an Introduction to Game Theory.* Oxford: Blackwell.

Reynolds, Craig W. (1987): Flocks, Herds, and Schools: A Distributed Behavioral Model. *Computer Graphics,* Vol. 21, No. 4, pp. 25-34.

Richardson, Lewis Fry (1960): *Arms and Insecurity.* Pittsburg: Boxwood Press.

Ripsman, Norrin M. – Levy, Jack S. (2008): Wishful Thinking or Buying Time? The Logic of British Appeasement in the 1930s. *International Security,* Vol. 33, No. 2, pp. 148-181.

Roberts, Gilbert – Sherratt, Thomas N. (1998): Development of Cooperative Relationships through Increasing Investment. *Nature,* Vol. 394, No. 6689, pp. 175-179.

Ruggie, John Gerard (1983): Continuity and Transformation in the World Polity: Toward a Neorealist Synthesis (Review). *World Politics*, Vol. 35, No. 2, pp. 261-285.

Ruggie, John Gerard (1993): Territoriality and Beyond: Problematizing Modernity in International Relations. *International Organization*, Vol. 47, No. 1, pp. 139-174.

Santos, Francisco C. – Pacheco, Jorge M. (2005): Scale-Free Networks Provide a Unifying Framework for the Emergence of Cooperation. *Physical Review Letters,* Vol. 95, No. 9, pp. 1-4.

Santos, Francisco C. – Pacheco, Jorge M. (2006): A new route to the evolution of cooperation. *Journal of Evolutionary Biology*, Vol. 19, No. 3, pp. 726-733.

Schelling, Thomas C. (1963): *The Strategy of Conflict*. New York: Oxford University Press.

Schelling, Thomas C. (1978): *Micromotives and Macrobehavior.* New York: W. W. Norton & Company.

Schuessler, Rudolf (1989): Exit Threats and Cooperation under Anarchy. *Journal of Conflict Resolution*, Vol. 33, No. 4, pp. 728-749.

Selten, Reinhard (1987): Evolutionary Stability in Extensive Two-person Games. *Mathematical Social Science,* Vol. 5, No. 3, pp. 269-363.

Selten, Reinhard – Hammerstein, Peter (1984): Gaps in Harley´s Argument on Evolutionarily Stable Learning Rules and in the Logic of "Tit for Tat". *Behavioral and Brain Sciences,* Vol. 7, No. 1, pp. 115-16.

Shubik, Martin (1970): Game Theory, Behavior, and the Paradox of the Prisoner's Dilemma: Three Solutions. *Journal of Conflict Resolution*, Vol. 14, No. 2, pp. 181-93.

Simon, Herbert A. (1996 [1969]): *The Sciences of the Artificial.* 3rd edition, Cambridge: MIT Press.

Singer, David J. (1987): Reconstructing the Correlates of War Dataset on Material Capabilities of States, 1816-1985. *International Interactions*, Vol. 14, No. 2, pp. 115-32.

Snidal, Duncan (1985): The Game Theory of International Politics. *World Politics,* Vol. 38, No. 1, pp. 25-57.

Snidal, Duncan (1991): Relative Gains and the Pattern of International Cooperation. *The American Political Science Review*, Vol. 85, No. 3, pp. 701-726.

Sugden, Robert (2004 [1986]) *The Economics of Rights, Cooperation and Welfare.* Houndmills: Palgrave Macmillan.

Taylor, Michael (1987): *The Possibility of Cooperation.* Cambridge: Cambridge University Press.

Taylor, Peter D. – Jonker, Leo B. (1978): Evolutionarily Stable Strategies and Game Dynamics. *Mathematical Biosciences,* Vol. 40, No. 1-2, pp. 145-156.

Tesfatsion, Leigh (2006): Agent-based computational economics: a constructive approach to economic theory. IN: Tesfatsion, Leigh – Judd, Kenneth J. (eds.): *Handbook of Computational Economics: Agent-Based Computational Economics, Vol. 2*. Amsterdam & Oxford: North-Holland, pp. 831-880.

Tesfatsion, Leigh – Judd, Kenneth J. (2006 eds.): *Handbook of Computational Economics: Agent-Based Computational Economics, Vol. 2.* Amsterdam & Oxford: North-Holland.

Trivers, Robert L. (1971): The Evolution of Reciprocal Altruism. *Quarterly Review of Biology,* Vol. 46, No. 1, pp. 35-57.

Udehn, Lars (2002): The Changing Face of Methodological Individualism. *American Review of Sociology*, Vol. 28, pp. 479-507.

Varoufakis, Yanis – Hargreaves Heap, Shaun P. (2004): *Game Theory: A Critical Text.* 2nd revised Edition, London: Routledge.

Wahl, Lindi M. – Nowak, Martin A. (1999): The Continuous Prisoner's Dilemma: II. Linear Reactive Strategies with Noise. *Journal of Theoretical Biology*, Vol. 200, No. 3, pp. 323-338.

Walt, Stephen M. (1994): *The Origins of Alliances*. Ithaca: Cornell University Press.

Walt, Stephen M. (1999): Rigor or Rigor Mortis? Rational Choice and Security Studies. *International Security,* Vol. 23, No. 4, pp. 5-48.

Waltz, Kenneth N. (1959): *Man, the State and War*. New York: Columbia University Press.

Waltz, Kenneth N. (1979): *Theory of International Politics.* New York: McGraw-Hill.

Watts, Duncan J. – Strogatz, Steven H. (1998): Collective dynamics of 'small-world' networks. *Nature,* Vol. 393, No. 6684, pp. 440-442.

Wæver, Ole (1997): The rise and fall of the inter-paradigm debate. IN: Steve Smith – Booth, Ken – Zalewski, Marysia (eds.): *International Theory: Positivism and Beyond.* Cambridge: Cambridge University Press, pp. 149-185.

Wendt, Alexander (1987): The Agent-Structure Problem in International Relations Theory. *International Organization,* Vol. 41, No. 3, pp. 335-370.

Wendt, Alexander (1992): Anarchy is what states make of it: the social construction of power politics. *International Organization,* Vol. 46, No. 2, pp. 391-425.

Wendt, Alexander (1994): Collective Identity Formation and the International State. *American Political Science Review*, Vol. 88, No. 2, pp. 384-396.

Wendt, Alexander (1999): Social Theory of International Politics. Cambridge: Cambridge University Press.

Wu, Jianzhong – Axelrod, Robert (1995): How to Cope with Noise in the Iterated Prisoner's Dilemma. *Journal of Conflict Resolution,* Vol. 39, No. 1, pp. 183-189.