Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Lecture with Computer Exercises:
Agent-Based Modeling and Social System Simulation

Project Report

Emergence of Cooperation with Stationary Leaders

Griffa Pietro & Hunhevicz Jens &
Kerstan Sophie & Stolle Jonas

Zurich
December 2019

Contents

1 Abstract

In this report, factors supporting the emergence of cooperation are studied from a game theoretical perspective by combining mechanisms and concepts previously identified in research. Social Learning Theory, real-world examples and findings from lab-based studies are used to enrich the basic reasoning for the conceptualization of the model's mechanisms. Precisely, imitation, migration, and leadership – the latter consisting of always cooperative behavior, reward, and punishment – are integrated. Our results indicate that leadership has a positive effect on the time it takes for the composition of the population to stabilize, although the overall contribution to the total numbers of cooperators next to imitation and migration are low. If, however, imitation and migration are weakened by lowering the probabilities of these behaviours, the effect of leadership is strong. The findings are discussed and related to future modeling possibilities of the emergence of cooperation.

2 Individual contributions

This project was realized by the team *cooperETHors*. The following four team members were involved and contributed equally:

- Griffa Pietro (18-951-285; griffap@ethz.ch) - MS Student
- Hunhevicz Jens (11-917-861; jenshu@ethz.ch) - Ph.D. Student
- Kerstan Sophie (18-959-627; skerstan@ethz.ch) - Ph.D. Student
- Stolle Jonas (17-942-699; jstolle@ethz.ch) - BS Student

3 Introduction

3.1 Context

The work was conducted as part of the course *Agent-Based Modeling and Social System Simulation* offered by the chair of computational social science (COSS) in the fall-semester 2019. The goal was to develop a project tackling techno-socio-economic challenges in application domains of complex systems using agent based modelling simulation. The focus-topic of our team *cooperETHors* was *04-emergence of cooperation*.

3.2 Motivation

The statements that our species' evolutionary success can be attributed largely to the ability and willingness to cooperate and that this is one of the most puzzling mechanisms in human and natural systems are definite. Nonetheless, they comprise a view that many academic disciplines from politics to economics and sociology to biology share [1]. Examples of voluntary cooperation are numerous and include resource sharing across international

borders in absence of a central authority or inter-organizational knowledge exchange to gain competitive advantage [1].
Yet, cooperation is a many-faceted phenomenon and from an evolutionary game theory perspective not as self-evident as the long list of conceivable real-world examples suggests. The case of cooperating in order to share and create “public goods” (i.e. goods that can be consumed by every member of a group irrespective of the individual’s contribution), while assuming a population of egoists and the absence of centralized control, is especially remarkable [2]. This phenomenon is often discussed in light of the social dilemma it depicts, which captures the circumstance that defection is tempting because it guaranties “the largest [possible] payoff regardless of what the others are doing” [3]. Precisely, the Nash Equilibrium lies at the non-cooperative state, making defection, for such a simple case, the “evolutionary stable” [4] strategy.
Due to the mismatch between this theorization and real-world occurrences, research has investigated mechanisms that enable the outburst, spread and preservation of cooperative behavior [4]. Despite these efforts, the nature of cooperation is not yet fully understood [3]. Partly, this is because the number of potentially discussable parameters is vast. Hence, there is still room to experiment with existing findings and examine the impact of certain single factors as well as their combinatory effects.

3.3 Background

Related to the issues outlined above, the emergence of cooperation has been studied extensively in lab experiments [5, 6] and by trying to simulate and model respective behaviors within grids [4] and networks [7]. A substantial fraction of this work has made use of evolutionary game theory as an underlying framework [8]. Along the most basic games matching this framework, are the classic two-player Prisoner’s Dilemma Game (PDG), or its alteration of placing these pairwise-interacting agents on a two-dimensional spatial grid, [4]. The herein positioned concept of the dominant strategy, i.e. the tenet that one behavioral option is generally better for players than any other option, is closely tied to the assumption of rationality on the part of the players.
However, humans don’t always decide and act rationally, but rather deploy varying strategies, follow divers goals and display certain inconsistencies in their actions [9]. Thus, microscopic model assumptions like (1) strategy alterations and adaptations rules, e.g. in form of behavioral imitation, (2) mobility, (3) altruism, and randomness have become matters of game theoretical frameworks, especially with regard to their macroscopic outcomes.

3.3.1 Findings on Imitation

In the early 1960s, Bandura and Walter published their first work on the Social Learning Theory (SLT). The core of SLT postulates that learning can derive from actively observing other people’s behavior and the related consequences to adjust one’s own actions, essentially by modeling (i.e. trying to replicate) the observed behavior [10]. In combination with elements of adaptation, this mechanism builds the foundation for several attempts within the literature to include imitation into PDG. Yet, the obtained results are highly contingent on the exact implementation of imitation [11, 4]. Hauert et al. [11] demonstrate that players' occasional and random choices of those to imitate, given a positive payoff difference, result in a replicator dynamic that displays only brief outbursts of cooperation. Contrary, the best reply strategy, assuming perfect information, produces a different oscillatory dynamic, which divides defectors, cooperators, and in their case loners into separated areas [11]. A further type of imitation, labeled as unconditional imitation, has been described as selfish short-sighted profit maximization [4]. It grants certain "focal" players the ability to analyze the strategies chosen and payoffs gained within their neighborhood to be able to adopt the strategy with the highest payoff. Unconditional imitation alone, however, is not successful in maintaining medium levels of cooperation: Defectors eventually dominate [4]. When paired with other mechanisms – e.g. either mobility [4] or altruistic punishment [12] – cooperation spreads and cooperators form resilient clusters.

3.3.2 Findings on Migration

Similarly to imitation, where preconditions in terms of availability of information about other players' strategies and payoffs exist, in order for players to be able to migrate, free space to move to has to be available. Given this is true, random migration to freely available space constitutes the simplest form of mobility, but has been shown to support defector invasion and therefore decrease cooperation [4]. Yet, thinking of more complex scenarios, e.g. the relocation of firms to specific sites like the Silicon Valley, points to the fact that mobility efforts are frequently exerted in order to eventually be surrounded by better and more prosperous environments or to at least forgo a current unsatisfactory situation [13]. In this manner, Helbing and colleagues [4] implemented success-driven mobility with the implication for players to move to neighborhoods with higher payoffs. Although even success-driven migration as a single mechanism cannot foster cooperation, it does so in combination with unconditional imitation described above [4].

3.3.3 Findings on Leadership

While imitation and migration have been widely recognized as mechanism within PDG, the specific construct and potential relevance of leadership has been added to the discussion more recently. The properties of leaders that game theoretical research has picked up on, e.g. from psychology research, include leaders' ability and power to inspire and engage, to handle conflict and foster adaptation [7]. Also, leadership can be meaningfully tied to SLT. When leaders' behaviors are observed by others, this reflects one of the theory's basic processes. Extending this comparison, leaders can be seen as role models, showing exemplary behavior, which might eventually be copied. Although this rational can add value to the discussion around cooperation, the implementation of exemplary (leadership) behavior in PDGs displays one of the two simplest strategies: Always cooperate (ALL C). In many games this strategy is opposing rationality. Yet, ALL C has been shown to survive even in laboratory experimental studies run over one month time with a prevalence of 40% [6]. Resilient cooperators name reasons for their behavior that overlap with principles of leadership. These can be summarized into altruistic motives, norm-based accounts, and long-term orientations. Because such cooperative behavior can easily be exploited by defectors, models pair ALL C with the ability to reward and/or punish other players' behaviors. This produces outcomes that show a substantial increase in cooperation [7].

3.4 Goal

The overarching goal of this project is to study factors that contribute to the emergence of cooperation by developing and testing an agent-based model based on game theoretical tenets. More precisely the following sub-goals constitute the basis of the project and report:

1. Replication of the core parts of Helbing and colleagues' [4] model and findings on the persistence and emergence of cooperation due to the combinatory effect of unconditional imitation and success-driven migration
2. Extension of said model by the concept of stationary leadership by example with inclusion of punishment and reward, referring to, but being qualitatively different from Wang and colleagues'; and Bahbouhi and Moussa's models [9, 7]

Whereas the replication of Helbing and colleagues' model [4] included in sub-goal I also functions as a validation of our own model, sub-goal II goes beyond pure replication and validation and tries to add meaning to the emergence of clusters of cooperators by implementing stationary leaders. We argue that leadership is not only a relevant mechanism to cooperation as outlined above, but further has the potential to explain where and why clusters of cooperators emerge. Our hypothesis therefore is, that the pattern of emergence of cooperators will be contingent on the positions of leaders on a two-dimensional grid.

4 Description of the Model

The underlying model assumptions are mainly based on the spatial game in Helbing et al. [4]. A grid of size $L \times L$ acts as the space where the behaviour of the individual agents is studied. The strategies are updated every time step Δt for a total of time steps t. The model assumptions about leadership (subsection 4.4) are based on Bahbouhi et al. [7].

4.1 Local interactions

In every round, each agent i (called focal player) interacts pairwise with a neighbor j in its neighborhood (so-called von Neumann neighborhood). The amount of interaction partners is denoted by m. Each binary interaction results in a certain payoff P_{ij}, which depends on the strategy of both agents. In the analysed model, each agent is either a cooperator (contributor) or a defector (free-rider). Even though the possibility to abstain from interactions is a realistic case and can promote cooperation (see e.g. Hauert et al. [11]), it is not considered here and could be investigated at a later stage. The payoff is then defined with the following payoff matrix:

$$P = P_{ij} = \begin{pmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{pmatrix} = \begin{pmatrix} R & S \\ T & P \end{pmatrix}$$

In the Prisonner's Dilemma, we have $P_{11} = R$; $P_{12} = S$, $P_{21} = T$, and $P_{22} = S$ with $T > R > P > S$. Mutual cooperation (reward R) gives a higher payoff than defection on both sides (punishment P). However, the highest payoff results for unilateral defection (temptation T), while the unilateral cooperation ends up with the poorest payoff (sucker's payoff S). In a single interaction ("one-shot game"), defections is always the better choice (Nash equilibrium). Therefore, everybody is expected to defect, leading to a phenomenon called "tragedy of the commons" (Hardin, 1968 [14]). The sum of all binary interactions in the neighborhood of size m of a focal player i with neighbors j for each time step Δt results in $P_i(t) = \sum_j P_{ij}$. Assuming $N < L^2$ agents, a density $\rho = N/L^2$ can be defined, giving us the ratio of occupied and free spaces in the grid. The strategy is updated in a random sequential way. That is in each iteration Δt, N focal players are randomly chosen one after the other. The respective focal player plays the Prisoner's Dilemma with all interaction partners in its defined neighborhood and determines the overall payoff.

4.2 Imitation

In the model, the agents apply an heuristic learning rule, in particular imitation. The focal player compares its own overall payoff with the overall payoffs that the neighboring agents reached at the time when these were randomly selected to play with their own von Neumann neighborhood. If the focal player reached the highest overall payoff, it sticks to its strategy. If not, it adapts to the strategy that resulted the highest overall payoff in the checked neighborhood with a probability $p_{imitation}$.

4.3 Success-driven migration

The kind of mobility implemented in the model is a "pull effect", so an agent tries to reach a certain location. Because this pull is caused by an expected higher overall payoff, one speaks of "success-driven" migration. To implement success-driven migration, the mobility range M is introduced. During the update procedure, the focal player can move to empty sites within the quadratic area of $(M * 2 + 1) \times (M * 2 + 1)$, e.g. for $M = 1$ to a quadratic area of 3×3. The highest expected payoff at other empty locations is determined by "test interactions". The agent moves to the new location with the highest expected payoff with a probability $p_{migration}$, and in case of multiple equivalent locations, to the closest one. At this location, the agent plays the Prisonner's Dilemma game with all its new von Neumann neighbors, collects its overall payoff, and imitates the strategy of the best performing neighbor (if there is a more successful one) (see Subsection 4.1).

4.4 Leadership

In Bahbouhi et al. [7], leadership in public good games were modelled in two ways: leading by example and leading with punishing. Both were shown to be effective ways to foster cooperation, the first less then the second. However, this behaviour was not considered in combination with imitation and success-driven migration. Furthermore, a complex (Barabási–Albert (BA) scale-free network model with preferential attachment [15], [16] was used instead of the spatial model. Here, the model assumptions for "leading by example" are implemented. For each Δt, a defined leader always cooperates in a first step, then the other agents play the game as describe in the previous sections. Furthermore, the leaders are stationary, i.e. they cannot move. This models leader's geographic positions, e.g. the Silicon-Valley case. The hypothesis is that there will be success-driven migration towards the leaders, reaching cooperative clusters faster and potentially of larger scale.
Since there is now an additional type of player (leader), the interactions with the leader need to be defined in an additional row ($i = 3$ - leader is the focal player) and column ($j = 3$ - leader is the neighbor) of the payoff matrix P. If the focal player i is a leader ($i = 3$), he always behaves as a cooperator when interacting with a neighbor j. Therefore, $P_{31} = P_{11} = R$ and $P_{32} = P_{12} = S$. If the focal player i cooperates ($i = 1$) with a leader ($j = 3$), he gets a higher payoff (incentive), so $P_{31} = x * R$, where x is a factor multiplying the defined positive payoff R for mutual cooperation. If the focal player i defects ($i = 2$) in an interaction with a leader ($j = 3$), he gets $P_{23} = 0$ payoff as a punishment. If two neighboring leaders interact ($i = j = 3$), the payoff for both is $P_{33} = P_{11} = R$, since they both always cooperate. This results in the following overall payoff matrix (leadership interactions depicted in bold letters):

$$P = P_{ij} = \begin{pmatrix} P_{11} & P_{12} & \boldsymbol{P_{13}} \\ P_{21} & P_{22} & \boldsymbol{P_{23}} \\ \boldsymbol{P_{31}} & \boldsymbol{P_{32}} & \boldsymbol{P_{33}} \end{pmatrix} = \begin{pmatrix} R & S & \boldsymbol{x * R} \\ T & P & \boldsymbol{0} \\ \boldsymbol{R} & \boldsymbol{S} & \boldsymbol{R} \end{pmatrix}$$

4.5 Noise

Since individual decisions are normally hard to predict, it is important to implement some sort of randomness or noise in the model. Furthermore, without noise it is likely that there is artificial history dependence and a sensitivity towards the initial conditions of the model [2]. Helbing et al. (2011) [4] introduce three different kind of noise. Here, random strategy mutations of an individual with probability q is considered, resulting in the opposite behaviour of what the imitation rule would predict.

5 Implementation

The model described in chapter 4 was implemented using *Matlab*. A pseudo-code can be found in the Algorithm-Representation 1, describing the interaction of the following files:

- *main.m*: In this file all relevant parameters are defined and all functions called. To reproduce the model, only this file needs to be executed. Comments on the parameters can be found in the code-file itself. The README gives further instructions on how to reproduce some of the results.
- *init.m*: A function that initializes the Prisoner's dilemma game with a grid of size $L \times L$ and density ρ, considering also the initial percentage of cooperators/defectors.
- *migration.m*: function with the main implementation of the Prisoners Dilemma game as described in Subsection 4.1. If leadership is considered, the file implements the described leadership behaviour of Subsection 4.4.
- *neighborhood_watch.m*: A function to get the sum of payoffs in the neighborhood of a player as described in Subsection 4.1.
- *success_driven_migration.m*: A function that explores the free spots around a player within the migration range M and checks if one is more profitable (using the function *neighborhood_watch.m*) by doing test interactions as described in Subsection 4.3.
- *imitate.m*: A function that updates the strategy of a player if another payoff in the neighborhood is more profitable as described in Subsection 4.2.
- *noise.m*: A function that introduces noise as described in Subsection 4.5.

All the code is described through comments in more detail in the respective files. Furthermore, the README gives instructions on how to reproduce some of the results. The output is a plot of the grid with the final constellation of cooperators (green), defectors (pink), and if activated, also leaders (blue). Additionally, the evolution of the number of cooperators and defectors, as well as the number of imitations is plotted for each Δt.

input : Grid of size $L \times L$, density ρ, number of time steps t, sample size N, neighborhood dimension m, mobility range M, initial ratio of cooperators, probability of migration/imitation $p_{migration/imitation}$, payoffs $T/R/P/S$, migration $true/false$, imitation $true/false$, leadership $true/false$, noise $true/false$

output: The final spatial grid with cooperators and defectors after all interactions.

```
initialization of the grid calling function init() with L and ρ;
for number of time steps t do
    call function migration();
    for sample size N do
        if leadership then
            stationary leaders always cooperate;
        end
        1) play the Prisoners Dilemma game with T/R/P/S and update payoffs;
    end
    2) sum up payoffs in each neighborhood m calling function
      neighborhood_watch();
    if migration then
        3) do test-interactions on empty slots within mobility range M;
        if an empty slot has a higher payoff then
            4) move to empty slot with higher payoff in mobility range M;
        end
    end
    if imitation then
        5) imitate strategy of highest payoff within neighborhood m calling
          function imitate();
    end
    if noise then
        6) apply noise calling function noise();
    end
    update data and grid;
end
plot grid by calling function plot_pop();
```

Algorithm 1: *high-level pseudo-code abstraction*

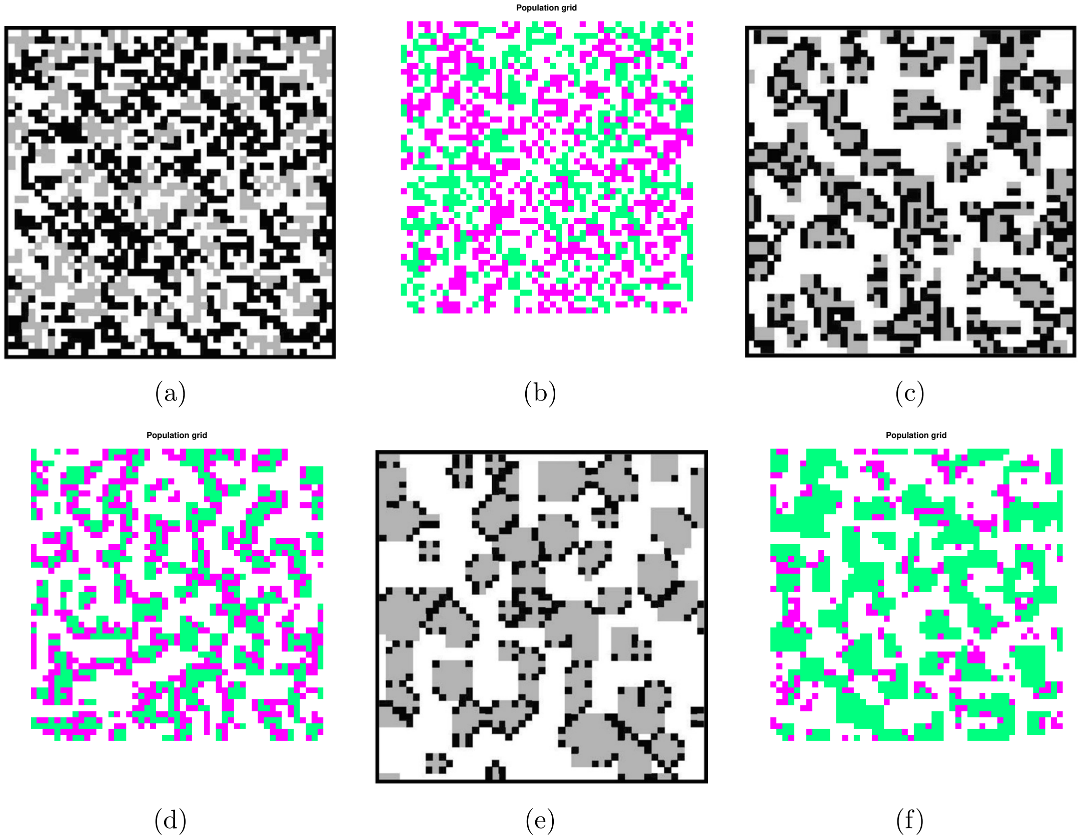

Figure 1: Comparison of our model (green: cooperators; pink: defectors) with the one of Helbing et. al. [4] (grey: cooperators, black: defectors) using the same parameters. Overall, the model is (approximately) able to reproduce the results for the shown combinations. Subfigure (a) and (b) is imitation only. Even though the Prisonners Dilemma suggests that all agents will defect at one point, imitation through local neighborhood interactions preserves a level of cooperation. Subfigure (c) and (d) show the result for success-driven migration only, leading to pattern formation. The agents Subfigure (e) and (f) is the combination of success-driven migration and imitation, which clearly leads to the highest level of cooperation. Iterations: $t = 50$. Grid size: $L = 49$. Initial cooperation: 50%. Payoffs: $R = 1, S = 0, T = 1.3, P = 0.1$. Density: $\rho = 0.5$. Neighborhood: $m = 1$. Migration range: $M = 2$. Probability for migration/imitation: $p_{migration/imitation} = 1$.

6 Simulation Results and Discussion

6.1 Model Validation

In order to validate the implemented model, some of the results of Helbing et. al. [4] were reproduced in Figure 1. Using the same parameters, the similar outcome indicates that the model is working properly. The results show that imitation in combination with success-driven migration lets cooperative individuals evade defectors and seek for a cooperative neighborhood. This leads to a high level of cooperative clusters, despite that the Nash equilibrium of the Prisonner's Dilemma is mutual defection.

6.2 Results of the Study

Knowing that the underlying ABM simulation works as in Helbing et al. [4], we study now the effect of leadership as introduced in Subsection 4.4 based on Bahbouhi et al. [7] in combination with success-driven migration and imitation. Some of the results are depicted in Figure 2 to explain the main mechanism. Most of the applied parameters are the same as for the replication in Subsection 6.1. Having said that, to show the effect of leadership more clearly, the payoff for the temptation T was set higher ($T = 2$, instead of $T = 1.3$) then in Helbing et al. [4]. In fact, the parameters used in Helbing et al. [4] lead to a very robust level of cooperation through imitation and success-driven migration. If the temptation to defect is set a bit higher, the effect still occurs (Figure 2, (a)), but needs more time to form (see Figure 2, (b)). The initial level of cooperation does not greatly effect the end-level of cooperation (e.g. only 10%, instead of 50%), but it takes more time to form the cooperative clusters. If we introduce leadership (keeping all the other parameters the same) (Figure 2, (c)), the effect on cooperation is negligible in terms of percentage of cooperation (Figure 2, (b) vs. (d)). Having said that, the clusters form faster (Figure 2, (b) vs. (d)) and around the leaders (Figure 2, (c)), whereas without leaders the location where they occur is random (Figure 2, (a)). However, the clusters without leadership show the same level of location stability then with leadership. Something that was quite surprising. This effect can be better observed in the time-laps videos in the Github-Repo[1] of the project. The effect of leadership becomes more obvious if the mechanisms of imitation and success-driven migration are weaker. To implement this, we set the probability of migration and imitation to $p_{migration/imitation} = 0.25$, instead of $p_{migration/imitation} = 1$ as in the previous case. Without leadership, cooperation decreases to very low levels (Figure 2, (e)/(f)). In contrast, the leaders maintain some level of cooperation around them (Figure 2, (g)/(h)). Cooperation sometimes occurs even further then the von-Neumann neighborhood, so not directly profiting from the incentivized payoff ($4 * R$) of the leader. Similar effects can be observed for other payoff and percentage combinations, but not all combinations were tested to investigate the sensitivity of parameters and the tipping points of the system.

6.3 Discussion

It is apparent from the results described in the preceding section that the objectives of (1) replicating parts of Helbing and colleagues' work and (2) including stationary leadership by example with inclusion of punishment and reward in this model have been accomplished

[1] https://github.com/PietroGriffa/Emergence-of-Cooperation/tree/master/videos

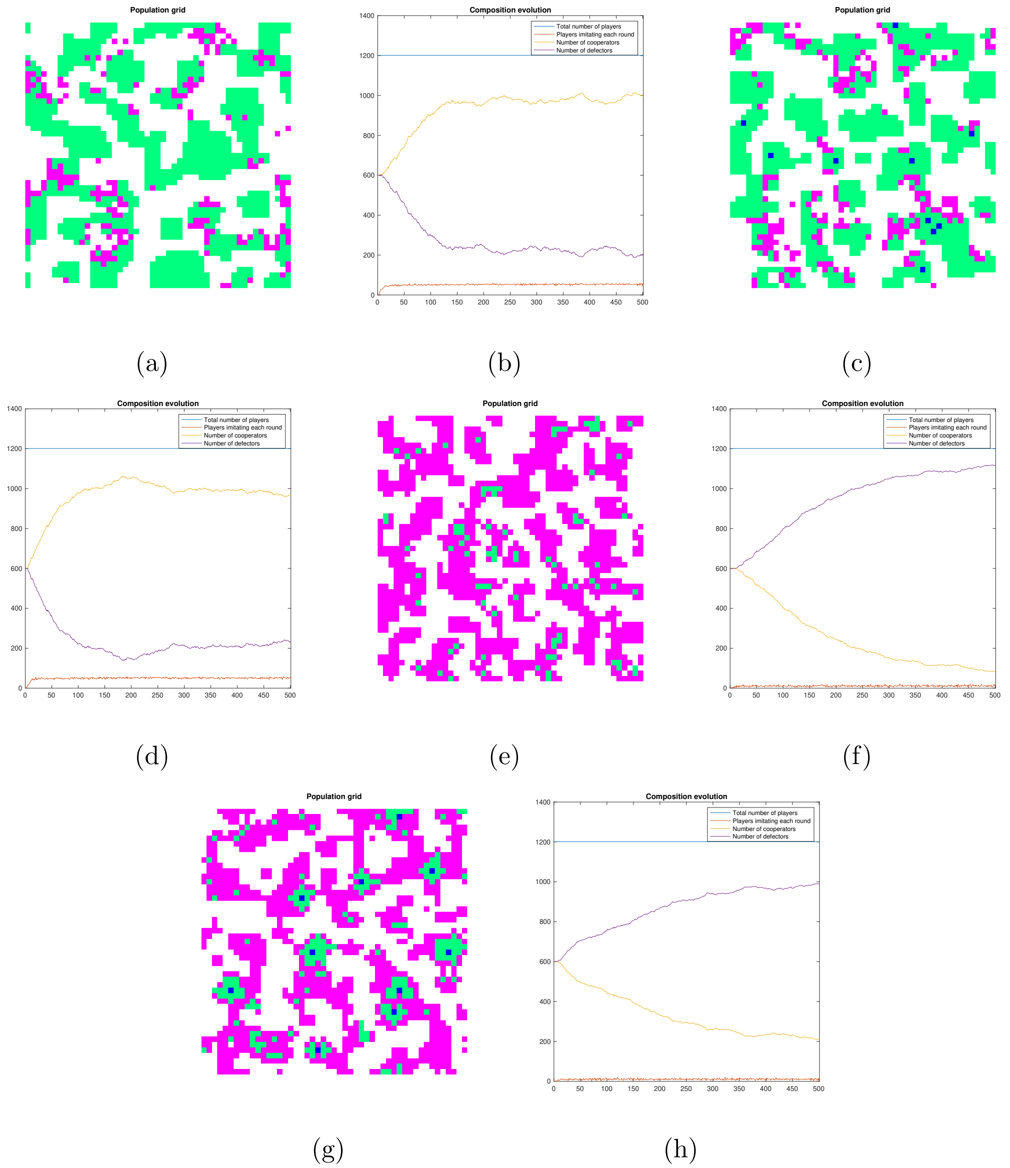

Figure 2: Comparing the effect of leadership ((c)/(d), (g)/(h)) versus only imitation and success-driven migration in ((a)/(b), (e)/(f)). Leaders: blue, cooperators: green, and defectors: pink. The effect of leadership is small, if the imitation and success-driven migration work well (a) to (d) - and large, if the other mechanisms are weak as in (e) to (f). Nevertheless, it seems that cooperation forms around the leaders even in case (c). Iterations: $t = 500$. Grid size: $L = 49$. Initial cooperation: 50%. Payoffs: $R = 1, S = 0, T = 2, P = 0.1$. Density: $\rho = 0.5$. Neighborhood: $m = 1$. Migration range: $M = 2$. $x = 4$, leading to a reward of $4 * R$. Case (a) to (d): $p_{migration/imitation} = 1$. Case (e)-(h): $p_{migration/imitation} = 0.25$.

successfully. By integrating the three different mechanism, we answer calls in the literature to combine multiple cooperation-related mechanism.
While our conceptualization of leadership in combination with imitation and migration results in a reduction of the number of rounds needed for the stabilization of a certain level of cooperation (initial distribution of cooperation set to 50%), leadership does not lead to higher levels of cooperation per se. However, once the probabilities for migration and imitation are turned from $p = 1$ to $p = 0.25$, leadership is more influential. Although defectors dominate in this scenario, leadership, compared to simulations including only imitation/migration, causes a less steep growth in the number of defectors, and seems to keep a comparably higher number of cooperators stably gathered around them. This does also directly relate to Helbing et al.'s [4] findings, which are argued to be stable for a specific range of parameter specifications, but in the present case only relate to high probabilities. Bringing to mind that the payoff matrix was adjusted quite drastically to make leadership work discloses one of the major limitations of the outcomes and dynamics described. Thus, the mechanism could be more likely attributed to punishment and reward than to the exemplary behavior in the form of cooperation that leaders show. Also, the levels of reward and punishment were defined in order for stationary leadership to work. It might be more scientifically reasonable to additionally try to identify the boundary payoff matrices for leadership to work, i.e. the minimum levels of required reward and/or punishment.
Beyond the variables included in this model, further mechanisms, like volunteering [11] or reputation [9], can lead to the emergence of cooperation.
Additionally, other frameworks and games have been used to model cooperation dynamics that have not been considered within this project. Among them are for instance the Snowdrift Game [13] or the possibility to implement the model within networks [7].
Notwithstanding these possibilities, the demarcation of sole mechanisms within the model presented turned out to already be so complex that handling even more parameters might not by all means be valuable. This is underlined by the fact that the results outlined above depict only a fraction of the insights that could possibly be gained from different parameter adjustments and combinations within the model.

7 Summary and Outlook

We implemented an existing model of unconditional imitation and success-driven migration into *Matlab* and additionally included exemplary stationary leadership with reward and punishment. The findings support a successful replication of major parts of Helbing and colleagues' model and the related outcomes. Additionally, we find support for the hypothesize that clusters of cooperators stably evolve around leaders.
The next step to build up on this project would be to systematically test all possible combinations of mechanisms with varying parameter settings. Generally, more research is needed to holistically include multiple cooperation-inducing mechanism. Whenever possible ad-

ducing real-world phenomena as the basis for future theorizing seems valuable from point research has currently reached. From a theoretical perspective, the SLT [10] is certainly only one of many highly practical theories from other discipline that can help in building agent-based models of cooperation and enrich game theoretical considerations.
Multiple questions around the emergence of cooperation are still unanswered, yet this project and report show that combining mechanisms, which were studied separately in previous research, provides interesting insights and makes advances to capture the complexity of the issues related to the emergence of cooperation.

8 References

[1] R. Axelrod. The Emergence of Cooperation among Egoists. *American Political Science Review*, 75(2):306–318, 1981.

[2] D. Helbing and W. Yu. The outbreak of cooperation among success-driven individuals under noisy conditions. *PNAS*, 106(10):3680–3685, 2009.

[3] F. Dercole, F. Della Rossa, and C. Piccardi. Direct reciprocity and model-predictive rationality explain network reciprocity over social ties. *Scientific Reports*, 9(1).

[4] D. Helbing, W. Yu, and H. Rauhut. Self-organization and emergence in social systems: Modeling the coevolution of social environments and cooperative behavior. *Journal of Mathematical Sociology*, 35(1-3):177–208, 2011.

[5] S. Duca and H. H. Nax. Groups and scores: the decline of cooperation. *Journal of The Royal Society Interface*, 15(144):20180158.

[6] A. Mao, L. Dworkin, S. Suri, and Duncan J. Watts. Resilient cooperators stabilize long-run cooperation in the finitely repeated prisoner's dilemma. *Nature Communications*, 8(1).

[7] J. Bahbouhi and N. Moussa. A graph-based model for public goods with leaderships. *Applied Mathematics and Computation*, 349:53–61, 2019.

[8] C. P. Roca, J. A. Cuesta, and A. Sánchez. Evolutionary game theory: Temporal and spatial effects beyond replicator dynamics. *Physics of Life Reviews*, 6(4):208–249.

[9] Z. Wang, T. Chen, and Y. Wang. Leadership by example promotes the emergence of cooperation in public goods game. *Chaos, Solitons & Fractals*, 101:100–105.

[10] A. Bandura and R. H. Walters. *Social learning and personality development*. Holt, Rinehart & Winston.

[11] C. Hauert, S. De Monte, J. Hofbauer, and K. Sigmund. Volunteering as Red Queen mechanism for cooperation in public goods games. *Science*, 296(5570):1129–1132, 2002.

[12] E. Fehr and I. Schurtenberger. Normative foundations of human cooperation. *Nature Human Behaviour*, 2(7):458–468.

[13] M. Perc and A. Szolnoki. Coevolutionary games - a mini review. *Biosystems*, 99(2):109–125.

[14] G. Hardin. The tragedy of the commons. The population problem has no technical solution; it requires a fundamental extension in morality. *Science (New York, N.Y.)*, 162(3859):1243–8, dec 1968.

[15] A.-L. Barabasi and Réka A. Emergence of scaling in random networks. *Science (New York, N.Y.)*, 286(5439):509–12, oct 1999.

[16] Réka A. and A.-L. Barabási. Statistical mechanics of complex networks. *Reviews of Modern Physics*, 74(1):47–97, jan 2002.

9 Appendix

ETH

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Declaration of originality

The signed declaration of originality is a component of every semester paper, Bachelor's thesis, Master's thesis and any other degree paper undertaken during the course of studies, including the respective electronic versions.

Lecturers may also require a declaration of originality for other written papers compiled for their courses.

I hereby confirm that I am the sole author of the written work here enclosed and that I have compiled it in my own words. Parts excepted are corrections of form and content by the supervisor.

Title of work (in block letters):

Emergence of Cooperation with Stationary Leaders

Authored by (in block letters):

For papers written by groups the names of all authors are required.

Name(s):	First name(s):
Griffa	Pietro
Hunhevicz	Jens
Kerstan	Sophie
Stolle	Jonas

With my signature I confirm that

- I have committed none of the forms of plagiarism described in the '<u>Citation etiquette</u>' information sheet.
- I have documented all methods, data and processes truthfully.
- I have not manipulated any data.
- I have mentioned all persons who were significant facilitators of the work.

I am aware that the work may be screened electronically for plagiarism.

Place, date

Zürich, 02.12.2019

Signature(s)

For papers written by groups the names of all authors are required. Their signatures collectively guarantee the entire content of the written paper.

Agreement for free-download

We hereby agree to make our source code for this project freely available for download from the web pages of the COSS chair. Furthermore, we assure that all source code is written by ourselves and is not violating any copyright restrictions.

Griffa Pietro	Hunhevicz Jens
Kerstan Sophie	Stolle Jonas