COMPLEX SOCIAL SYSTEMS SEMINAR

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EXPLORING THE EMERGENCE OF COOPERATION

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Abstract

Cooperation emerges in complex, globalized societies even when individuals have different incentives to cooperate. In this study, we explore conditions under which cooperation emerges in a society which is mobile, spatially organized, and/or constituted of heterogeneous individuals. To this end, we start with the model developed in Helbing et al. 2009 and then further refine it to make it more representative of the society we live in. We refine the model in two broad directions. First, taking inspiration from Maslow's hierarchy of needs, we make the population structure heterogeneous and incorporate asymmetry in the payoffs of the Prisoner's Dilemma. Second, we place our individuals on a small world network and study the impact of the network topology on the emergence of cooperation. Our results highlight that imitation and migration lead to cooperation even in highly heterogeneous societies where individuals have different incentives to cooperate and defect. This is mostly due to imitation of winning strategies. Societies which better fulfill the needs of their individuals show significantly higher levels of cooperation. Small-world networks can increase cooperation through hub effects, if the accessibility of these hubs is limited and an initial share of cooperators is present in these hubs.

Keywords: Cooperation, Maslow's Hierarchy of needs, Small world networks

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1. Introduction

1.1 Emergence of cooperation

A large range of societal problems - spanning from climate change, criminality, to over-fishing - are characterized by a lack of cooperative behaviour between actors due to incentives to free-ride [16, 39]. In these situations, cooperation comes at a cost to themselves. Free-riders benefit from the altruistic behaviour of other actors, while not paying the cost of cooperation. This situation has been formalized in game theory as the 'Prisoner's Dilemma' [2, 3]. Under the Prisoner's Dilemma standard paradigm, two players have a choice between cooperation and defection, and the payoff from defecting, in the case the other decides to cooperate, is larger as the payoff due to mutual cooperation. When players only interact once (non-repeated game), defectors largely dominate cooperators. Yet, when players repeatedly interact with each other, a cooperator can use strategies to avoid being defeated by defectors [20]. In an iterated Prisoner's Dilemma, a situation of stability (the so-called Nash equilibrium) emerges when no player can improve their payoff if no other player switches their strategy. Yet, the assumption of hyperrational individuals evaluating different strategies when interacting with each other, as well as of the assumption of complete and perfect information, do not necessarily hold, as proved from findings from behavioural economics [17]. It also does not explain the spontaneous emergence of cooperation in a broad spectrum of biological systems, most of which - such as insects colonies - could hardly be argued to be constituted of rational organisms [29]. The discipline of evolutionary game theory hence developed to investigate the mechanisms underlying emergence of cooperation [38, 43].

In dynamic evolutionary games in finite populations, strategies which are more fit tend to emerge by selection although they are exposed to the probability of being invaded by mutant strategies opposed by selection [31]. If a simple iterated Prisoner's Dilemma is played, defection is a more evolutionary fit strategy and the global cooperation level rapidly drops to around 10% [6]. Yet, a series of mechanisms can increase cooperation, such as reciprocity [41], reputation [32, 8], punishment [10, 37]. Recently, game theory started recognizing the importance of spatial structures and dynamics for the emergence of cooperation. Network structures have ambiguous effects on cooperation, since on their own they cannot really foster cooperation [22, 7, 15, 13] without a "critical mass" of initial cooperators [34]. Yet, the opportunity to interrupt interactions with defecting neighbours leads to the emergence of cooperation clusters. This phenomenon is described by network reciprocity [30, 33]. As underlined in [1], the structure of the networks and its influence on interactions and dynamics between its individuals can differently affect the emergence of cooperation. A specific type of network (the small-world network), well describing many real-world networks, recently entered evolutionary game theory showing to promote, given an initial critical mass of cooperators and an optimal degree of network heterogeneity, the spread of cooperative behaviours through hub effects [34, 28, 12]. The combination of two mechanisms which in themselves do not lead to increased cooperation, migration and imitation of neighbours' successful strategies, also leads to increased cooperation [18, 19]. This highlights the fact that complex social systems and their cooperative behaviour can not be understood by single silver-bullet mechanisms. Instead, feedback loops and complex dynamics exist between different mechanisms, and their combination is needed to obtain insights applicable to real world societal systems [19].

1.2 The role of imitation and migration

The rather surprising, spontaneous outbreak of cooperation in a noisy world of selfish, rational individuals was observed in [18] and [19]. The world comprised of unrelated individuals, with no reputation or option of voluntary contribution. The individuals solely looked after their own interests by employing success-driven migration and imitation of strategy of the best performing individuals. Cooperative clusters of players emerge from the combination of learning by observation (*imitation*) and by success-driven relocation of players (*migration*). Migration alone drives spatial pattern formation, but does not increase the total share of cooperation, and imitation rather breaks cooperation. Under both mechanisms separately, with the introduction of noise (random strategy mutations and random relocations) cooperation dramatically breaks, leading to a robust invasion by defectors. Yet, combining the two mechanisms not only leads to the formation of cooperative clusters and to a large majority of cooperators, but is also robust against noise. This work primarily highlighted the importance of mobility in the establishment and maintenance of cooperation. This is at odds with what one might expect from replicator equation dynamics, wherein cooperative clusters were found to be unstable to invasion by defectors [9]. These findings suggest that, combined with the ability of strategic social learning, the possibility to move to increase one's pay-off underlies the formation of local cooperation.

1.3 Small world networks

In the last two decades, the field of network science has emerged as an extremely useful tool to investigate complex systems. The reason for this is the discovery of complex networks - networks with characteristic topological features. The two main milestones of the field are the discovery of scale-free networks [4] and the discovery of small-world networks [42]. Here, we will examine the second class of complex networks - that of small-world networks.

To understand this type of network we first need to define some quantities used in network science. Firstly, the degree of a node is the number of edges the node belongs to while the distance between two nodes is the shortest path connecting them. Using these, the clustering coefficient can be defined in many different ways but generally speaking it expresses a measure of the tendency of nodes to cluster together.

Small-world networks are networks whose nodes have small average distance but large clustering coefficients. The way they are usually constructed is using the Watts – Strogatz model. Using as hyperparameters the number of nodes N, the mean degree k and a parameter p called probability of rewiring, we construct a ring where each node is connected with k neighbours. Then, for every edge, we rewire it with probability p choosing randomly a different node from the initial pair of nodes of that edge. Their interesting property for this project is that they have many hubs (i.e. high degree nodes) due to the rewiring process as shown in figure 1.1.

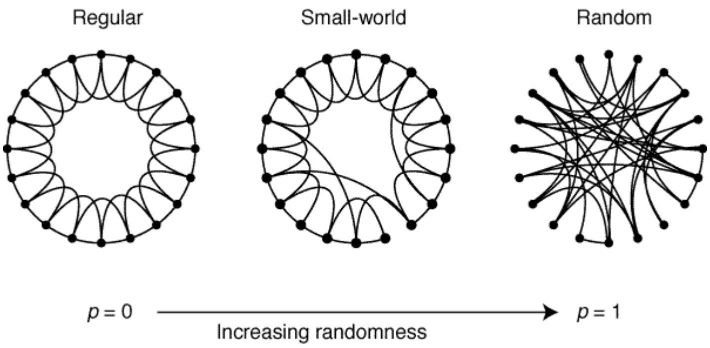


Figure 1.1: Small-world networks with mean degree $k = 4$ and total nodes $N = 20$ for different probabilities of rewiring. Notice the high number of hubs at the locations of the rewiring.

The relevance of networks for evolutionary game theory became clear in the early 2000s [33]. In fact, interactions of individuals in real societies do not take place, as often modeled in spatial Prisoner's Dilemma games, in flat space. Although in [7] a laboratory experiment with real individuals showed that three types of networks (local, random, and small-world networks) all led to low levels of cooperation, with lowest levels in small-world networks, new insights from modelling of small-world networks have showed that this largely depends on the structure of the network itself [34, 12, 28]. Small-world networks moreover offer an excellent topography to test the robustness of mechanisms enhancing cooperation, such as reciprocity [30, 33], reputation [8], and success-driven migration and social learning [18].

1.4 Asymmetric Prisoner's Dilemma and Maslow's Hierarchy of Needs

Societies are not composed of individuals that equally profit from cooperative and defective behaviours. Due to social stratification, individuals might have different incentives to cooperate or defect. Social stratification can be seen as the result of the different level of satisfaction of individual needs. Moreover, our entire societal structure i.e. concepts of law and order, justice, capitalism, socialism and democracy, has sprouted due to the complexity of human needs and the interaction of these needs of individuals. Societies differently satisfying their individuals are radically different. The level of cooperation within broader groups can be strongly associated with the level of satisfaction of their individuals, as noted by Scheller [35] for neighborhoods. This has hence a relevance for real-world social dilemmas, such as international negotiations on climate change, in which a Prisoner's Dilemma type of game is played by individuals (corresponding to nations) with different levels of satisfaction of their needs. For example, least-developed countries might still have difficulties to provide for the fulfillment of the basic physiological, health, and safety needs of their citizens and might see the environment as a less important problem than highly-industrialized societies with a large per-capita income, where nature has a higher importance due to its intrinsic and recreational value.

In psychology, Maslow's hierarchy of needs, proposed by Abraham Maslow in [25] in 1943, stands as one of the most famous content theories of human motivation. Maslow had sought to develop a theory of human motivation, seeking to encapsulate the complex experience of being human into a simple pyramid-like structure - wherein, each level represents a distinct human need, ranging from basic physiological needs to those of esteem and self actualisation. This model, which received serious critiques even by

Figure 1.2: Maslow's pyramid of human needs

Maslow himself [21, 27, 26], originally described a step-wise advance within the pyramid. Needs lower down in the hierarchy had to be satisfied before individuals could attend to needs higher up. Maslow himself recognized that the fulfillment of needs is not an "all-or-none" phenomenon [27] and that needs lower down in the hierarchy can be only partially satisfied while the individual attends to higher needs. However, the model provided a conceptual starting point to understand human motivation in different disciplines, underpinning for example the Post-Keynesian theory of consumption [40, 23].

The theory potentially has a relevance in game theory, which is currently not explicitly explored in the literature. In fact, following Maslow's models, the motivations underlying interactions between individuals with different levels of fulfillment result in asymmetric games, where different players have different incentives to cooperate or defect. For example, we can assume that if physiological needs are not satisfied, the motivation to defect (and hence receive a potentially higher payoff) is greater than for a player which has belonging and love needs, and hence a higher incentive to cooperate. This results in an Asymmetric Prisoner's Dilemma game. Previous studies on asymmetric games, based on a simple distinction between low and high-payoff players, showed that asymmetry significantly decreases cooperation, as low-payoff players are more likely to defect after mutual cooperation [36, 5]. The underlying mechanism is that players are concerned with relative outcomes rather than maximization of their own outcomes if they have information about the other player's payoff after an interaction with them [36]. A more complex model was proposed by Guo et al. [15], which started off from the observation that populations are often divided into sub-groups, and that within the subgroup they might play a symmetric Prisoner's Dilemma, while when interacting with other groups the payoffs are asymmetric resulting in different games played (harmony, snowdrift, stag-hunt games). As a general rule, the lower the dilemma strength between sub-populations, the larger the share of cooperators.

1.5 Objectives

In this study, we explore the combinations of different mechanisms that could lead to cooperation (imitation of successful behaviours, success-driven migration, and small-world networks), which represent characteristics of local interactions in a globalized world. We explore the case in which the game played is an asymmetric Prisoner's Dilemma game to simulate conditions closer to the real world. We argue, in fact, that simplifying societies to an ensemble of homogeneous individuals with the same utility functions compromises the external validity of Prisoner's Dilemma games. To build our asymmetric Prisoner's Dilemma, we assume that different individuals have different incentives to cooperate or defect depending on their level of satisfaction of needs as described in the Maslow's hierarchy of needs [25]. By distinguishing individuals based on the level of need they want to fulfill, we attempt to incorporate elements of the human psyche into our model. Since different socio-political and economic systems differently provide for the fulfillment of needs of societies, our study aims at gaining insights into the interlinkages between different socio-economic systems and the levels of cooperation observed.

2. Model

2.1 Basic model

Taking inspiration from the model used in [18], we started with a similar grid of individuals with the following features:

- Each individual has two strategies: to either **cooperate (C) or Defect (D)** and he gets a payoff depending on what he and his neighbours decide to do.
- The payoff matrix for interaction with one neighbour looks as follows:

P1 / P2	C	D
C	R, R	S, T
D	T, S	P,P

  where, **R=Reward for mutual cooperation, T=Temptation to defect, S= Sucker's payoff, P=Punishment for mutual defection**. For the Prisoner's Dilemma (PD), $T > R > P > S$ and $2R > T + S$, so select appropriate values for these parameters

- We created a lattice with L^2 sites, placed N individuals on it and randomly assigned strategies (C or D) to each individual

- Next, we randomly selected an individual, say individual j, and made him interact with m neighbours (m=4 in the paper) and calculated the payoff P_i for each interaction and then the overall payoff = $\Sigma_{i=1}^{m} P_i$
- Similarly, we calculated the overall payoff of each of the m neighbours
- Thereafter, individual j:
  - **imitates** the neighbour with the highest overall payoff with probability 1-r or
  - **randomly resets** his strategy with probability r. Further, probability for resetting to C is q and for resetting to D is 1-q ($q << 1$). This represents poor imitation or trial and error by the individual.
  - **undergoes success-driven migration step**: Before imitation, the individual explores empty sites in his Moore neighbourhood of size ($2M+1 \times 2M+1$) and moves to a spot that offers a better overall payoff. In case of same payoff, he moves to the closer spot.
- We carry out this procedure for all other players sequentially in a random order, and then iterate this until "equilibrium' reached. This we determine by observing the fraction of cooperators and stopping our simulation when this fraction does not change significantly over time.

2.2 Extension I: Heterogeneous population structure

We implemented the influence of a heterogeneous population by using an asymmetric Prisoner's Dilemma game, as opposed to the standard one with symmetric payoffs. We encoded individuals using binary strings ($\sigma = \sigma_1\sigma_2\sigma_3\sigma_4\sigma_5$) of length 5 ($\because$ there are 5 levels on the pyramid), with each character in the string representing a level in the pyramid shown in figure 1.2 and the leftmost character (σ_1) representing the lowest level i.e. physiological needs and so on. $\sigma_i = 1$ implies fulfilment of the ith need and $\sigma_j \le \sigma_i$ for $j > i$, due to the assumption of sequential fulfilment of needs. Therefore, while 11000 is a valid individual in our model universe, 00011 is not because we assume that a person cannot have self fulfilment needs satisfied without satisfying their physiological needs.

Now, the payoffs of the individuals must depend on which level they are on in Maslow's pyramid, so we modified the payoff matrix in the following way:

P1 / P2	C	D
C	β_1R, β_2R	γ_1S, α_2T
D	α_1T, $\gamma_2 S$	δ_1P,δ_2P

where, α, the multiplicative constant that modifies the T must be inversely proportional to the sum of the needs because higher the level of individual satisfaction, lower the temptation to defect, β, the multiplicative constant that modifies the R must be proportional to the sum of the needs because higher the level of individual satisfaction, higher the reward for cooperation, γ, the multiplicative constant that modifies the S must be proportional to the self fulfilment needs because the higher these needs are, the less it hurts to be a sucker, finally, δ, the multiplicative constant that modifies the P must be proportional to the psychological needs because the higher these needs are, the worse it feels to be uncooperative. Surely, the dependence of these multiplicative modifiers on the individual's needs are debatable and there is more than one way to define these. Our definitions here are solely based on intuition and our understanding of human behavior. In future research, the definitions of these multiplicative constants could be empirically assessed by inferring them from the relationship between levels of satisfaction of individuals and their personal incentives to cooperate or defect in an experimental setting.

Our definitions give us the following multiplicative multipliers:

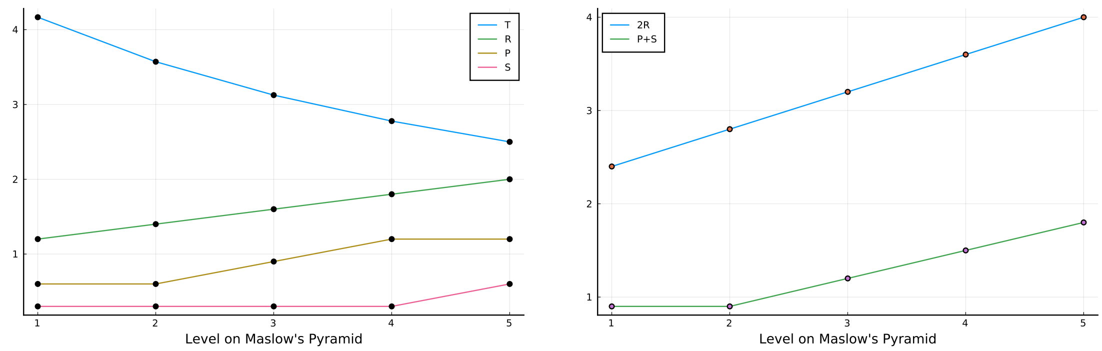
$$\alpha = \frac{2}{1 + \frac{\Sigma_{i=1}^{5}\sigma_i}{\Sigma_{i=1}^{5} i}} \tag{2.1}$$

$$\beta = 1 + \frac{\Sigma_{i=1}^{5}\sigma_i}{\Sigma_{i=1}^{5} i} \tag{2.2}$$

$$\gamma = 1 + \sigma_5 \tag{2.3}$$

$$\delta = 1 + \frac{(\sigma_3 + \sigma_4)}{2} \tag{2.4}$$

Note that these have been defined such that all the multipliers lie between 1 and 2. Further, the original payoffs were chosen such that the new payoffs still satisfy $T' > R' > P' > S'$ and $2R' > P' + S'$. It is clear from figure 2.1 that as an individual gets higher up on the pyramid, his payoffs get more clustered together.



(a) T>R>P>S at all levels

(b) 2R>P+S at all levels

Figure 2.1: The variation in the payoff values as a function of the level of the pyramid. Original (T,R,P,S)=(2.5,1,0.6,0.3)

We initialised our population by randomly assigning needs to individuals by fixing a probability of fulfilment of needs and the conditioning the existence of higher needs upon the existence of lower needs.

2.3 Extension II: Dynamics on small world networks

We simulate more realistic spatial interactions by implementing the Prisoner's Dilemma played by individuals located on a static small-world network instead of a 2D grid. We aim at investigating the implications of the hubs on the final outcome. We make the following assumptions:

- The network structure does not change in time. That means that each individual can only change their strategy and not their edges with others. This is initially a reasonable assumption since a lot of networks in biology, sociology or engineering are small world networks even though they could change proving that they are in equilibrium (equilibration).
- Each individual imitates only their neighbours and therefore has no knowledge of the whole network structure (locality).
- Each time step is Markovian: The individuals have no memory of whom they collaborated with before (no reputation).
- There is no migration. We assume that all nodes are occupied by players who either collaborate or defect (no migration).

We created a small-world network with number of nodes N, mean degree k and probability of rewiring p and we distributed randomly N/2 cooperators and N/2 defectors. Then, just as on the grid, a random node plays the Prisoner's Dilemma game with their neighbours, collecting a specific payoff. This payoff is compared with those of the player's neighbours (of which - unlike for the grid - there can be more than four) and the player imitates the most successful neighbour. This process is repeated until the equilibrium as stated previously.

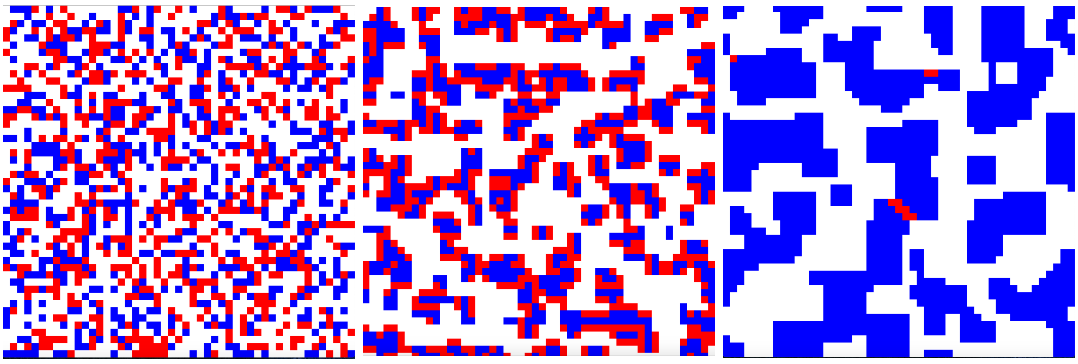
Unlike in model 2.1, every node of the lattice is not dynamically speaking equivalent. The players placed on or near hubs are expected to follow different behaviours to the ones in branches. This complicates the first step when we take a random initial configuration of cooperators and defectors since now every initial configuration is not equivalent to the rest. To overcome this, for every network, we sample many random initial configurations. We expect that for a sufficiently high number of samples we can make comparisons of the effect of the structure of each network with respect to the equilibrium result.

3. Results

3.1 Validation of basic model

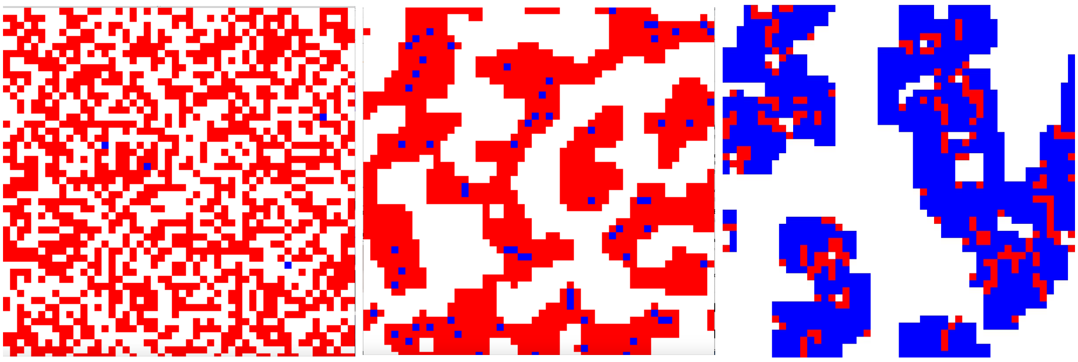
We were able to successfully implement the model described in [18] and reproduce the results, as a sanity check.

In figure 3.1, we can appreciate the impact of migration, in establishing cooperative clusters with defectors at the boundaries. Moreover, in the absence of noise, migration and imitation interact synergistically to produce large-scale clusters of cooperation. So in a perfect world, where people can always successfully imitate the best performers, cooperation appears easy to attain.



(a) Imitation only (b) Migration only (c) Imitation and migration

Figure 3.1: The fraction of cooperators (in blue) and defectors (in red) in a system with no noise i.e. random strategy mutations



(a) Imitation only (b) Migration only (c) Imitation and migration

Figure 3.2: The fraction of cooperators (in blue) and defectors (in red) in a system with noise i.e. no random strategy mutations

However, in the real world, people often experiment with strategies and cannot always emulate the best performers; this is encoded using the noise of random strategy mutations. This noise really puts to test the establishment of cooperation, as can be seen in figure 3.2. Here, neither imitation nor migration alone can establish cooperation. However, they come together in an interesting way to produce dynamic cooperative clusters, even in the presence of noise.

3.2 Effect of heterogeneous population

To start off with, we used the same probability p of unfulfillment of needs, for all the needs in the pyramid. Therefore, the probability that needs on e.g. level 3 are satisfied $=(1-p)^3$ because needs on level 3 are conditioned upon needs on the earlier two levels. The resulting population structures are shown in figure 3.3.

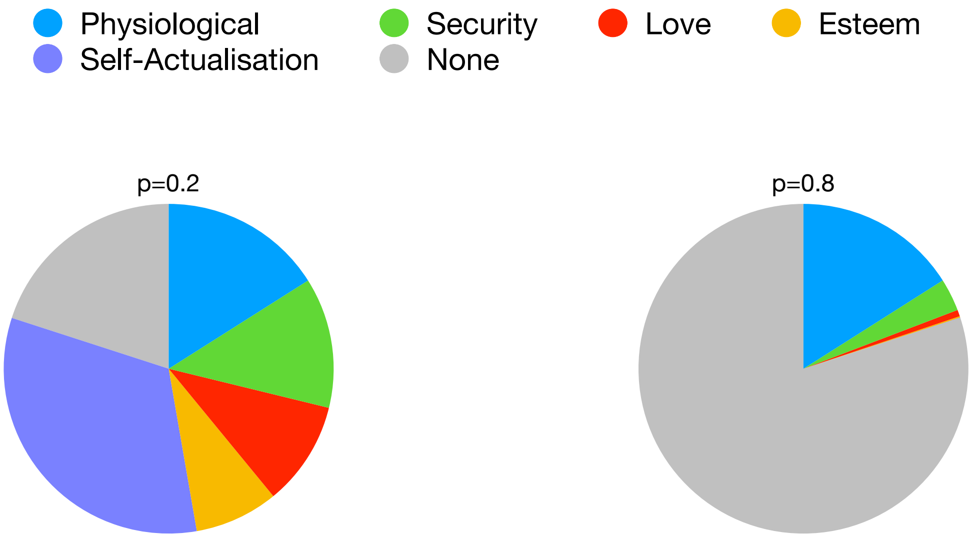


Figure 3.3: The different population structures that can result from our paradigm of assignment of needs. Shown here for two different values of p, $p = 0.2$ and $p = 0.8$.

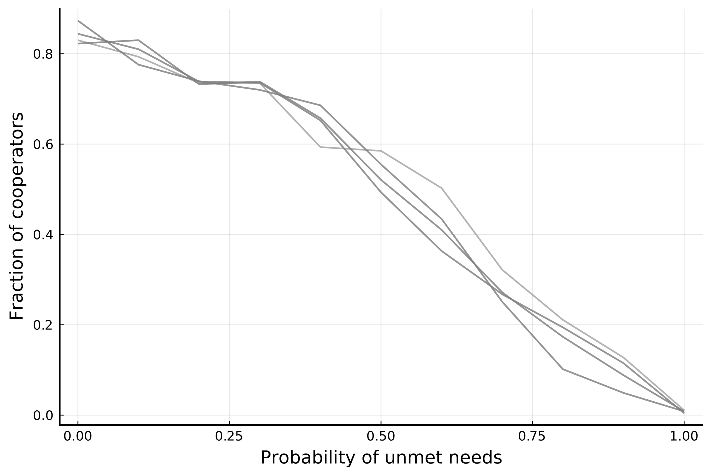
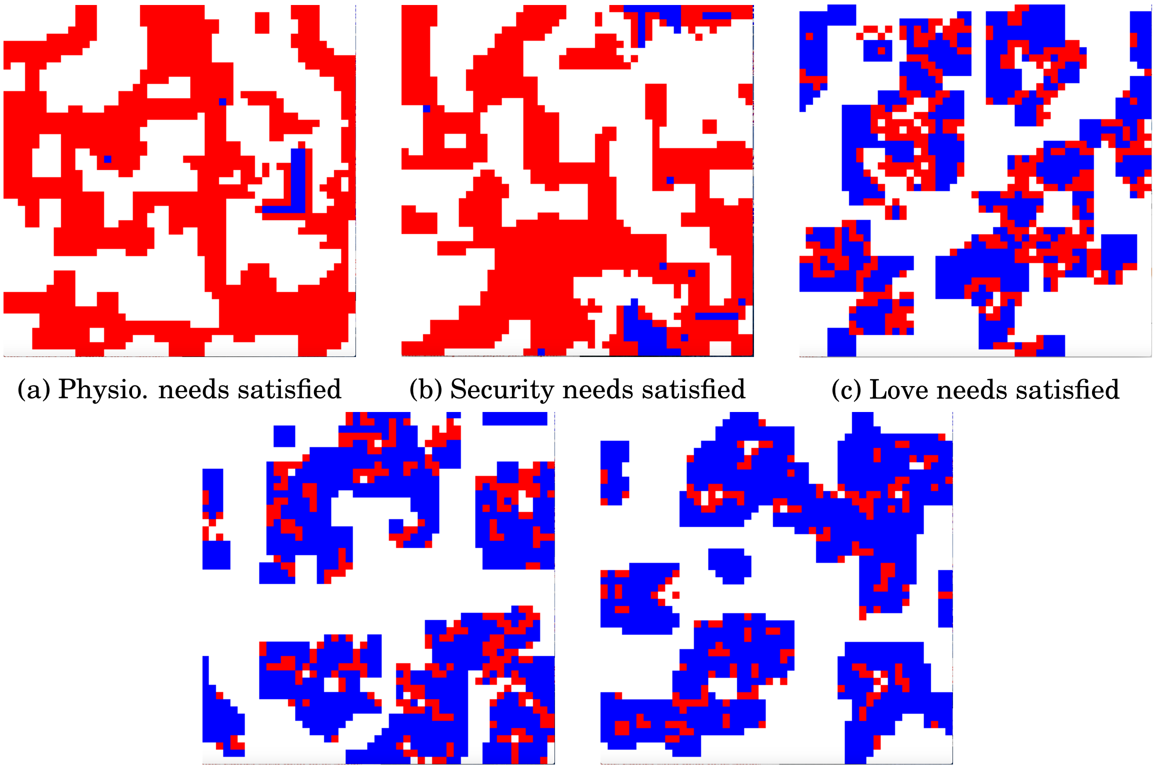


Figure 3.4: The dependence of the fraction of cooperators on the probability of unmet needs, p. The individual curves show replicates of the same computational experiment. The significant overlap of curves shows that there isn't much variance in this result.

Using this paradigm, we studied the dependence of the fraction of cooperators at equilibrium on the value of p. This is shown in figure 3.4. For very small values of p, i.e. high probability of met needs, the majority of our population attains self actualisation and this results in a significantly higher degree of cooperation. On the contrary, in populations where the majority has all needs unmet, defectors reign.

Next, we wanted to study the merits of having heterogeneous populations and asymmetric Prisoner's Dilemmas, in comparison to the generic case with a homogeneous population structure and symmetric games. To do this, we first studied homogeneous populations composed of individuals belonging to only one level of the pyramid. The



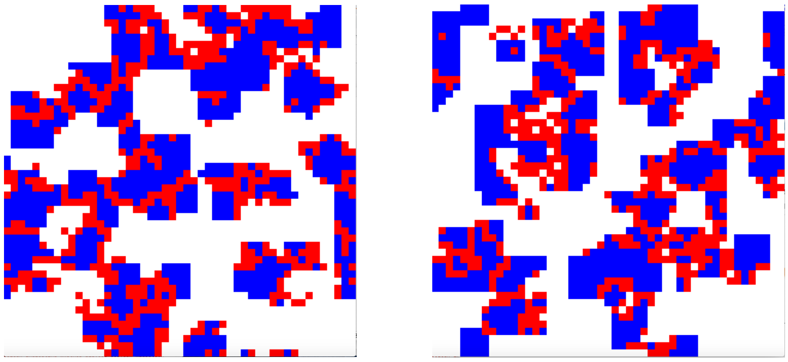
(a) Physio. needs satisfied (b) Security needs satisfied (c) Love needs satisfied

(d) Esteem needs satisfied (e) Self actualisation

Figure 3.5: The fraction of cooperators (in blue) and defectors (in red) for the different homogeneous populations belonging to Maslow's pyramid. $T = 2.1, R = 1, P = 0.3, S = 0.1$. Notice that the cooperators like to flock together, even when in minority, while defectors remain solo or in small groups when in minority.

results of this are summarised in 3.5. While individuals belonging to the first two levels of the pyramid fail to cooperate, large scale cooperative clusters can be seen for individuals belonging to the third and higher levels of the pyramid. Moreover, the fraction of cooperators grows as higher needs are met and increases from roughly 0.7 to 0.9 as we go from level 3 to level 5. This is pretty much in keeping with what we expected from the nature of the modified payoffs (figure 2.1). Further, the size of the clusters are much larger than what we observed in figure 3.2 despite the presence of noise. This is interesting and suggests that emergence of cooperation causes the population to coalesce and form agglomerations and thus get closer, as opposed to being scattered all over the space. Finally, it is also very interesting to note the small cooperative clusters that formed in figures 3.5 (a) and (b), as opposed to the behavior that defectors show when they are in minority (see figures 3.5 (c), (d) and (e)) , perhaps indicating that cooperators like to flock together, even when in minority, while defectors show more "lone-wolf" like tendencies.

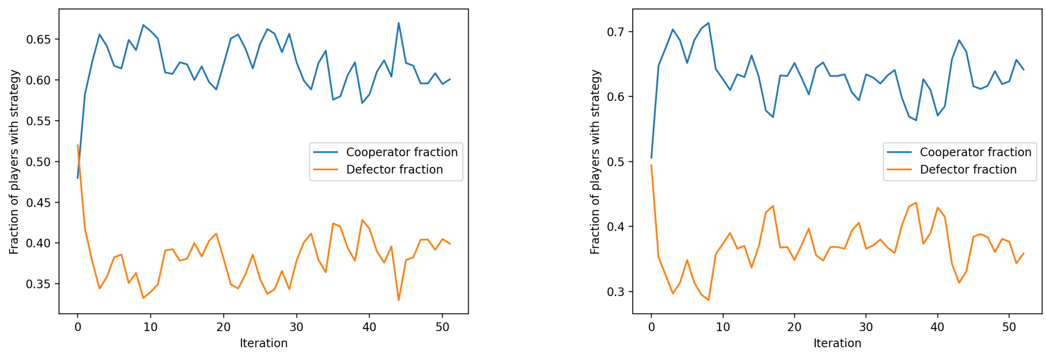
Lastly, it is important to realise that real societies comprise of individuals that do not have even their basic needs met. Can we then see large scale cooperation in such societies? This is the question we addressed, by fabricating a maximally heterogeneous population i.e. a population with maximum entropy and studying the evolution of cooperation in it. The results are shown in figures 3.6 and 3.7. It is pleasantly surprising that the maximally heterogeneous population shows very similar behavior to the homogeneous one. This indicates that the existence of some individuals from the higher levels of the pyramid enables even those individuals that wouldn't have cooperated in their homogeneous groups to cooperate due to imitation. This highlights the importance of "role models" in a society, who the other individuals emulate in hope of getting higher payoffs.



(a) Fraction of cooperators (blue) and defectors (red) in a maximally heterogeneous population i.e. it is composed of equal fraction of individuals from each level.

(b) Fraction of cooperators (blue) and defectors (red) in a homogeneous population comprising of individuals from level 3 (love needs satisfied) of the pyramid.

Figure 3.6: Emergence of cooperation in heterogeneous vs. homogeneous populations. $T = 2.1, R = 1, P = 0.3, S = 0.1$



(a) Fraction of cooperators as a function of time in a maximally heterogeneous population i.e. it is composed of equal fraction of individuals from each level.

(b) Fraction of cooperators as a function of time in a homogeneous population comprising of individuals from level 3 (love needs satisfied) of the pyramid.

Figure 3.7: Emergence of cooperation in heterogeneous vs. homogeneous populations. $T = 2.1, R = 1, P = 0.3, S = 0.1$

3.3 Effect of network topology

We simulated games with imitation, with and without noise, and without migration. We also assumed that every node of the network is either a defector or a cooperator. An example of a simulated small-world network is shown in figure 3.8.

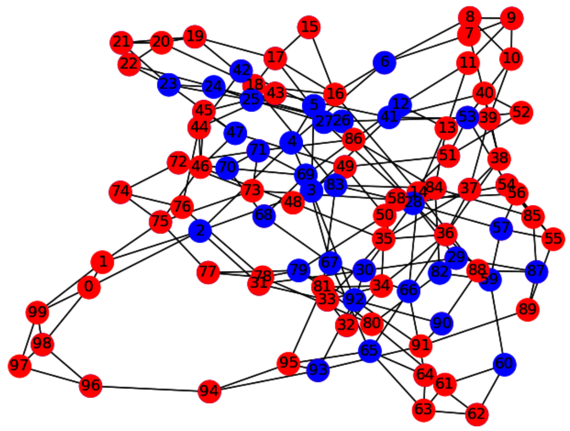
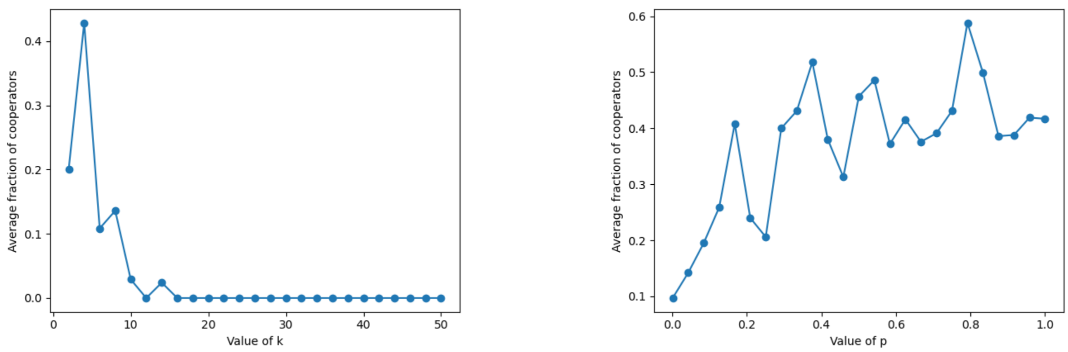


Figure 3.8: Example of a small-world network with 100 nodes, mean degree is 4 and probability of rewiring is 0.2. The red and blue nodes are the defectors and cooperators respectively. This snapshot is at zero time iteration and thus with approximately equal number of defectors and cooperators.

The main effects of the network topology are due to the existence of hubs. Specifically, as shown in figure 3.9a, we found that for constant probability of rewiring and number of nodes and without noise, the higher the mean degree, the less likely it is for cooperators to prevail in the end. On the other hand, in 3.9b, we found that for constant number of nodes, no noise and constant mean degree, the higher the probability of rewiring, the more likely the cooperators dominate.



(a) The average fraction of cooperators in equilibrium versus the mean degree of the small-world network. Number of nodes is 100, the probability of rewiring is 0.05 and number of iterations 5000 (sufficiently high to reach equilibrium). For each k, we sample 20 different cases and the average of their fraction of cooperators is calculated.

(b) The average fraction of cooperators in equilibrium versus the probability of rewiring of the small-world network. Number of nodes is 100, the mean degree is 8 and number of iterations 5000 (sufficiently high to reach equilibrium). For each p, we sample 10 different cases and the average of their fraction of cooperators is calculated.

Figure 3.9: The fraction of cooperators for different variables of small-world network without noise and without migration.

These results verify the hypothesis that hubs enhance cooperation as long as they are not much accessible. In particular, as presented in figure 1.1, the sites of rewiring

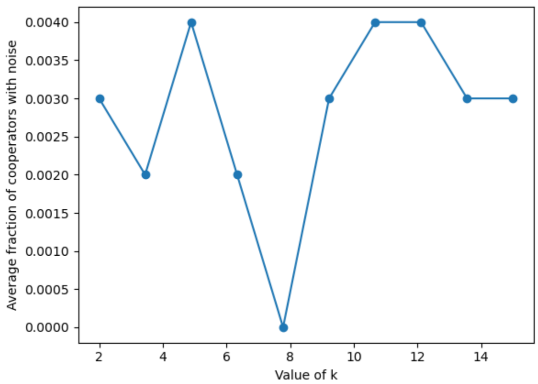


Figure 3.10: The average fraction of cooperators with noise in equilibrium versus the mean degree of the small-world network. Number of nodes is 100, the probability of rewiring is 0.05 and number of iterations 5000 (sufficiently high to reach equilibrium). For each p, we sample 10 different cases and the average of their fraction of cooperators is calculated.

can be seen as hubs and therefore the higher the probability of rewiring, the more prevailing the effect of the hubs is. In addition, if the mean degree is small, the inner nodes in the hub are disconnected from the rest of the network. Therefore, if there is initially a small number of cooperators in a hub, they are more likely to withstand defectors because the inner nodes only have cooperator neighbours and therefore they continue imitating cooperators. On the other hand, the nodes near the edge of the hub are vulnerable to defectors. The existence, thought, of inner cooperators combined with the condition $2R > T + S$ increases their chances staying cooperators.

In order to understand whether the hubs are robust or not, we allowed noise in our simulations. The results are presented in figure 3.10. We see that compared to the noiseless case in 3.9a, the existence of noise destroys completely any cooperator hubs. This means that hubs are fragile and vulnerable to defectors in the presence of perturbations.

A possible extension would be to explain in the first place why in the initial configuration there are cooperator hubs and why the network of interactions has the specific form. In our model, we did not allow migration because migration in networks is usually presented using adaptive networks- networks with nodes with ability to control their edges- rather than moving on empty nodes in an already pre-structured network. This would make the model much more complicated because the game dynamics would affect the structure and vice versa. Therefore, a possible extension of our analysis would be to allow the nodes to make connections strategically with other individuals.

Nonetheless, we may expect that the final structure is a small-world network as it is shown in [44] and [14]. Besides, small-world networks are found in many co-evolutionary situations in real world networks such as biology, sociology and technology and therefore it is reasonable to hypothesize that they may be the equilibrium network form. However, the lack of robustness as shown above means that this is only half of the story. Nature requires robust structures due to continuous perturbations and therefore we expect the final co-evolved network to have extra properties. Indeed, in [44], it is shown that the evolved network tends to have hierarchical structures besides small-world like properties in order to boost its stability. The hierarchical relations imply that a more useful tool for studying the emergence of cooperation may be higher-order networks such as multi-layer networks or hypergraphs where the games are played between groups-layers instead of individuals.

4. Conclusions and discussion

Our study shows that the mechanism explored in [18, 19], of imitation and success-driven migration, leads to enhanced cooperation, also under conditions closer to the real-world ones.

When coupled with a more realistic population which has different levels of needs, if individuals can imitate the strategy of more successful players and move around to maximize their payoffs, cooperation still emerges. Under these conditions, cooperation is strongly dependent on the average level of fulfillment of the needs of the population. A population with unsatisfied individuals cannot interact cooperatively. A possible real world corollary of this, can be that needs of individuals must be met sufficiently for communism to exist successfully and the only conceivable way to do that would be through a initially capitalist society. This observation echoes what was reported in [11]: "theories of communism and capitalism do not need to be considered opposites or alternatives, but rather systems that satisfy different stages of humanity's technological development". On a more technical front, our results need to be compared with [24], where the authors found that asymmetric payoffs in prisoner's dilemma do not lead to enhanced cooperation. This is contrary to what we observed in our spatial models with the a population structure dictated by Maslow's pyramid of needs.

Imitation of successful strategies, coupled with chances of rewiring (which is a type of random migration), also increases cooperation in small-world networks. This is mostly due to hub effects (low mean degree k and high probability of rewiring p). If there is an initial number of cooperators in the hub (what the literature defines as "critical mass" [34]), cooperators tend to survive invasion by defectors as long as hubs are not too accessible (hence the need for low mean degree). Nodes at the center of a hub always show cooperative behaviour, whereas external nodes are more likely to defect. Our small-world network did not include success-driven rewiring (adaptation, which is the network equivalent of success-driven migration) nor a heterogeneous population. Further research could combine these elements, to test the impacts of the two cooperation enhancing mechanisms, in a setting closer to the real world.

Authorship

All authors contributed to this work in an equally important manner. Y.A. implemented the code. N.B. performed literature review, conceived the algorithm underlying the asymmetric Prisoner's Dilemma, wrote the report, and presented the results. N.P. reviewed literature, conceived the small-world network, implemented it in the code, performed the related analysis, and wrote the report. M.S. conceived the idea of an asymmetric Prisoner's Dilemma, performed the related experiments, wrote the report, and presented the results. H.U. implemented the code and presented the results.

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