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Follow Flee: A Contingent Mobility Strategy for the Spatial Prisoner's Dilemma

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Abstract: *This paper presents results from a series of experimental simulations comparing the performances of mobile strategies of agents participating in the Spatial Prisoner's Dilemma game. The contingent movement strategies Walk Away and Follow Flee are evaluated and compared in terms of (1) their ability to promote the evolution of cooperation, and (2) their susceptibility to changes in the environmental and evolutionary settings. Results show that the Follow Flee strategy outperforms the Walk Away strategy across a broad range of environment parameter values, and exhibits the ability to invade the rival strategy. We propose that the Follow Flee movement strategy is successful due to its ability to pro-actively generate and maintain mutually cooperative relationships.*

1 Introduction

Mobility is a key factor in solving the puzzle of the evolution of cooperation. Intuitively, this is due to the fact that the individuals of a population prefer to interact with, and indeed benefit from interacting with, cooperative players rather than interacting with those who would try to exploit them. Mobility is a form of network reciprocity [14] that allows agents to respond to their current neighbourhood by moving within their environment; this movement can be random or reactive. These movements may also be classified as local or global. The inclusion of movement creates a more realistic framework than those adopted in some of the traditional, static, spatial models [15]. Models where agents are allowed to move are typically more intuitive, and create better analogies to human and animal behaviour. The role of mobility in the evolution of cooperation has grown in importance and recognition in recent decades, from researchers in the domains of evolutionary game theory, theoretical biology, physics, sociology, and political science. It has gone from being perceived as a hindrance to the emergence of cooperation to one of its primary supporters. While unrestrained movement can, and does, lead to the 'free rider' effect [5], allowing highly mobile defectors to go unpunished, simple strategy rules or mobility rates significantly curb this phenomenon allowing self-preserving cooperator clusters to form, and cooperation to proliferate. Mobile strategies play a vital part as mechanisms for the emergence, promotion, and sustainability of cooperation.

Several mechanisms for the emergence of cooperation exist, but all essentially express a need for cooperators to either avoid interactions with defectors or increase and sustain those with other cooperators. Research in this domain is largely divided into two categories based on their categorisations of mobility; all movement should be random [18, 12], or that movement is purposeful or strategically driven, but may indeed contain random elements [1, 8]. The *Follow Flee* strategy [6] enables agents to increase their percentage of mutually cooperative interactions by pursuing other cooperators and avoiding defectors. Specifically, as the name suggests, it allows players to form and sustain clusters by following nearby cooperators, and by fleeing from invading defectors.

In this paper, we investigate a form of contingent mobility for agents participating in a Spatial Prisoner's Dilemma – the *Follow Flee* strategy – and present a comparison to the *Walk Away* strategy proposed by Aktipis and others [1, 10]. We adopt an evolutionary model whereby agents obtaining higher payoffs in the Prisoner's Dilemma replace those with lower payoffs. Both strategies first compete on their own against a *Naïve* (or random) strategy and are then evaluated together. We discuss the relative performance of both strategies, and highlight the limitations of *Walk Away* as a movement strategy. This strategy is studied in a range of environments while varying a number of parameters including population density, and some evolutionary settings. We will demonstrate that *Follow Flee* outperforms *Walk Away* at every level of comparison, and does so with quite a large margin. We hypothesise that this is due to *Follow Flee*'s ability to maintain mutually cooperative, spatial relationships despite the pressure from defectors, and its ability to effectively maximise an agent's potential payoff.

The paper is laid out as follows: we review related work of mobility in the Spatial Prisoner's Dilemma in the next section. Section 3 outlines our methodology, including a description of the environment, agent representation, and the evolutionary mechanism. In Sect. 4, we present and discuss a number of experiments and results regarding the performance of agent strategies. Finally, we present our conclusions and suggest future avenues for this research.

2 Related Work

Evolutionary game theory has been studied since the 1980s when John Maynard Smith incorporated ideas from evolutionary theory into game theory [11]. Traditionally, spatial evolutionary game theory involved the study of evolutionary games where a participant's interactions were constrained by a particular static topology, such as a lattice [15]. The Prisoner's Dilemma [3], and its extensions in the iterated form, is the game most often studied in this domain. It has attained such popularity due to its succinct representation of the conflict between individually rational choices and those made for the common good. In this context, mobility was seen as a hindrance to the emergence of cooperation, leading to the creation of 'free riders'. These individuals always defected and could move quickly between, and exploit, cooperative clusters without repercussion. The work of Enquist and Leimar [5] only considers agent mobility at an individual or micro level without considering the macro effect of how a cluster of cooperators may become robust from invasion by the 'free riders'. Subsequent research into the effects of mobility on the evolution of cooperation is divided into two broad categories: contingent movement [1, 7, 8, 19], and non-contingent or random movement [18, 12, 2].

Aktipis in her seminal paper [1] presents a contingent movement strategy for playing the spatial iterated prisoner's dilemma. Here, agents employ the simple movement rule *Walk Away* to disconnect from defecting partners by relocating to a local random cell, and to continue cooperative partnerships by staying still. Agents form pairs and repeatedly interact together when they meet in the environment, which is quite discordant with contemporary and subsequent environments. The strategy allows cooperators to take advantage of mobility rather than it being only beneficial to defectors. The main appeal of this strategy is its simplicity; agents are memoryless but *Walk Away* is still sufficient for cooperation to spread and dominate. In this paper the strategy is tested and shown to be effective against itself, *Tit-for-Tat* [3], and a spatial version of the *Win-Stay-Lose-Shift* [13] strategy. The key behind its success is that this form of mobility allows agents to avoid repeated interactions with defectors and maintain links with other cooperators without employing complex strategies. *My Way or the Highway (MOTH)*, the work of Joyce et al. [10], follows and extends Aktipis' *Walk Away* idea. The authors present a model that replicates Axelrod's tournament with the addition that players may conditionally refuse to participate in playing the game. One criticism that can be made of these models is that they do not attempt to maintain those crucial mutually cooperative pairings under pressure from defector invasion.

Contingent mobility also has the capacity to be proactive where individuals deliberately seek better neighbourhoods, rather than simply reacting to stimuli and randomly relocating. The works by Helbing and Yu [8, 9] describe a form of contingent movement called *Success Driven Migration (SDM)*, which forms one of the most influential and important ideas within the scope of mobility. In this model, individuals can test potential sites for migration, both local and global, in order to discover neighbourhoods with the highest expected payoff. The authors demonstrate that cooperation can become dominant in a migratory population as it allows individuals to find other cooperators creating clusters, and to avoid defectors. The main appeals of *SDM* lie in its ability to establish cooperation, and its realism; it has a better narrative for real-world migration than diffusion or random models. *SDM* has been shown to generate spatial correlations between cooperators, even under noisy conditions, giving cooperative clusters the ability to regroup following invasion or dispersal. Buesser et al. [4] offer an extension to the *SDM* model that investigates systematically both the interaction and migration radii. The authors reveal that widespread cooperation is best obtained when agents interact locally in a relatively small neighbourhood. However, both these models are limited in that they incur high memory and complexity costs.

Random mobility can be used to describe the minimal conditions for the evolution of cooperation, and is the preferred template of many researchers. Vainstein et al.[18] wrote perhaps one of the most influential papers in this domain. It explores the minimal conditions for sustainable cooperation using a spatially structured population on a diluted lattice using unconditional, memoryless strategies with non-contingent movements in the context of the prisoners's dilemma. The authors have shown, for the first time, that cooperation is possible in the presence of mobility when the available space is somewhat reduced and that "intermediate mobilities enhance cooperation!"[18]. The authors deduce that at higher densities, and with moderate mobility, clusters of cooperators invade defectors. This work is further expanded upon to include the Stag Hunt game [16], and later a complete phase diagram of the temptation to defect, with transition lines, is constructed [17]. Meloni et al. [12], another prominent study, introduce an alternate random movement model in which prisoner's dilemma players are allowed to move in a two-dimensional plane.

There has been much success in this field to date with evidence even suggesting that migration mechanisms are more influential on the prevalence of cooperation than on the strategy update model used by individuals [4]. The area of non-contingent movement has been well studied, and the area of contingent mobility has also received a lot of attention. However, in our opinion, there is scope for a simple movement strategy that is guided by the rule "Cooperators attract - Defectors repel" [18], but also employs only minimal complexity. Additionally, there has been little success in establishing the outbreak of cooperation in the presence of high mobility levels; a more proactive migration strategy could be the key to unlocking this final puzzle.

3 Methodology

In the following sections we will describe the environmental settings, agent representation, game parameters, and evolutionary dynamics used to build the model for simulation.

3.1 Environment & Agent Representation

We use the standard parameters of the Prisoner's Dilemma game (see Tab. 1) for agent interaction as endorsed by Sicardi et al [16]. The strategy with which agents play will be fixed; either always cooperate or always defect. We choose to implement pure strategies in order to emphasise the relevance of mobility in this context. The population of N agents inhabit a toroidal shaped diluted lattice with $L \times L$ cells, each of which can be occupied by up to one agent.

Table 1: The Prisoner's Dilemma

	C	**D**
C	3,3	0,5
D	5,0	1,1

We use the same values for N and L as used in the work of Aktipis [1] (see Tab. 2). However, we do deviate from the Aktipis setup in that we enforce the restriction of one agent per cell, and expand the interaction radius of agents. We did not adopt these particular rules because they deviate so far from the traditional spatial setup and in our opinion, are not properly justified as they confer a large advantage to any two cooperators who are placed in the same cell. The interaction and movement radii of agents is determined using the Moore neighbourhood of radius one. This comprises the eight cells surrounding an individual in a cell on the lattice. The agents can only perceive and play with those within this limited radius. At each time step, agents participate in a single round of the Prisoner's Dilemma with each of their neighbours, if any. Agents are aware of the actions taken by their partners in a single round, but these memories do not persist. Following this interaction phase, agents have the opportunity to take one step into an adjacent free cell according to their movement policy. Movement will not occur if there is no adjacent free space, or if their strategy dictates that they remain in their current location. Isolated agents will take one step in a random direction.

3.2 Movement Strategies

Three movement policies are employed for this study: *Follow Flee*, *Walk Away*, and *Naïve*.

3.2.1 Follow Flee

has two rules that are applicable to any neighbourhood combination. These are (1) move to a cell adjacent to a neighbouring cooperator, and (2) move to a cell non-adjacent to a nearby defector. These rules combine when both agent types are present. This strategy emerged as a result of a study that used a genetic algorithm to co-evolve mobility and cooperation [6].

3.2.2 Walk Away

instructs agents to (1) move to a cell non-adjacent to nearby defectors, or (2) stay still to continue to interact with neighbouring cooperators. The first rule takes precedent when both agent types are present. This strategy was first proposed by Aktipis [1], and later by Joyce et al. [10].

Table 2: Experimental Parameters

Symbol	Description	Value
L	Length of Lattice	25
N	Size of Population	100
s	Time Steps per Generation	15
r	Reproduction Rate	25

3.2.3 Naïve

agents employing this strategy move to an empty adjacent cell without regard to the actions of its neighbours.

3.3 Evolutionary Dynamics

The reproduction and death mechanisms of this study will be determined by two variables: r and s. The number of time-steps per generation is determined by s; the sampling rate; and the number of agents replicated after each generation is determined by r; the reproduction rate. In a single generation, agents will accumulate their payoffs received from playing the Prisoner's Dilemma with their neighbours. This will be used as a measure of fitness. At the end of each generation, the agents are ranked according to their fitness score. The bottom $r\%$ will die and the top $r\%$ will replicate themselves, passing on both their movement and C/D strategies. In this way, the population size will remain constant. These offspring will be placed randomly on the grid. The older agents remain in the same place, thus maintaining any spatial clustering between generations. Following reproduction, the fitness score of the whole population will be reset and a new generation will begin.

4 Experimental Results

In this section we will describe the experimental set up and results of the four experiments developed to compare and contrast the performances of the strategies *Follow Flee* and *Walk Away*. In the first instance, we perform a baseline experiment in which both strategies compete separately against the *Naïve* strategy. In the second experiment, we expand upon the baseline by varying both the number of time steps per generation (s), and the reproduction rate (r), over a wide range of values. Next, we continue the comparison by varying the grid size to investigate the effect, if any, of density on the outcome of a simulation. Finally, both the *Follow Flee* and *Walk Away* strategies are directly compared, competing in the same simulation without the influence of the *Naïve* strategy. To obtain a sufficient sample each simulation is run 100 times.

Table 3: Exp. 1 Average Results vs. Naïve

Strategy	% Cooperator Wins	Convergence	# Cooperative Interactions
Walk Away	28%	202 timesteps	328,000
Follow Flee	97%	380 timesteps	382,000

4.1 Experiment 1: Follow Flee and Walk Away vs. Naïve

In this experiment we run two sets of similar simulations, one with *Walk Away* the other with *Follow Flee*, comparing their respective performances against the random strategy *Naïve*. The population of agents is placed randomly on the $L \times L$ torus, and the strategies are assigned in equal proportion. A single simulation will last 1000 time-steps, in which the population of 100 agents will take 15 steps each generation. The distribution of spatial strategies, level of cooperation, the time taken for the simulation to converge on cooperation (or defection), and the total number of interactions will all be recorded. As is shown in Tab. 3, *Follow Flee* vastly outperforms the *Walk Away* movement strategy in terms of enabling cooperation to emerge and dominate the population. Against the *Naïve* strategy, the *Walk Away* strategy only induces cooperation in 28% of simulations, whereas in this environment, the *Follow Flee* strategy leads to cooperative outcomes in 97% of the simulations. This is surprising because in the original work Aktipis' strategy achieved dominance in 100% of simulations against a similar naïve strategy. The simulations testing *Walk Away* typically converge on a solution more quickly than *Follow Flee*. This huge difference is probably due to the change in environmental conditions; we do not allow two cooperators to co-exist in the one cell and remain removed from any potential interaction with defectors. This modification perhaps ilustrates how important this constraint was in Aktipis' original paper in inducing cooperation. Our strategy generates on average 15% more mutually cooperative interactions than Aktipis' and this is most significant in the early generations when defectors are more prevalent.

4.2 Experiment 2: Varying the Evolutionary Dynamics

In this experiment, we vary the parameters r, the reproduction rate (number of individuals replaced), and s, the number of time-steps per generation, of the model while testing the success of both *Follow Flee* and *Walk Away* as in the previous set up. Success is measured in terms of the strategy's ability to induce cooperation among the population. The length of a simulation is increased to 5000 time-steps to ensure that the population converges on a solution. The values $s = \{5, 10, 15, 20, 25\}$ and $r = \{3, 6, 9, 12, 15, 18, 21\}$ are investigated, with a separate set of simulations, as per Experiment 1, carried out for each pair of values. In each simulation agents will either take an increased number of steps per generation or a larger proportion will participate in the evolutionary process.

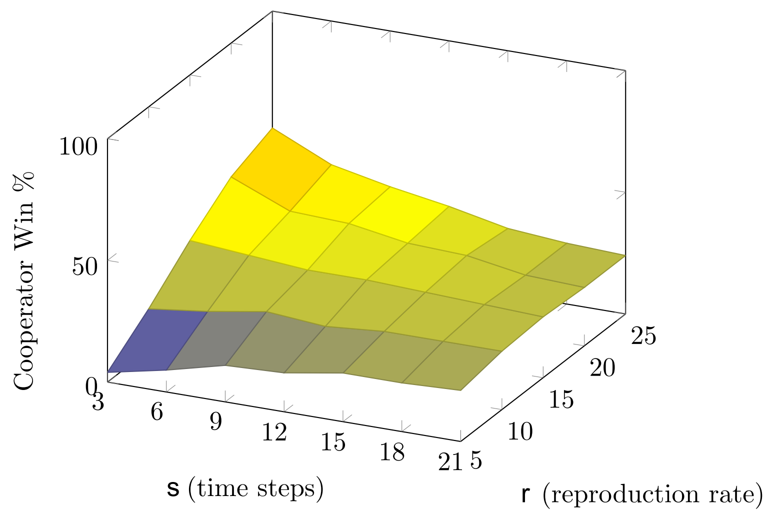

Figure 1: *Walk Away* vs. *Naïve*: Varying the Evolutionary Dynamics.

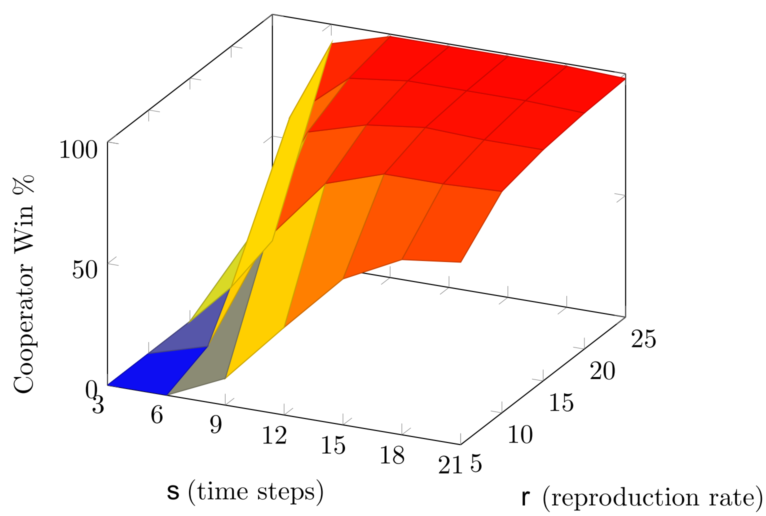

Figure 2: *Follow Flee* vs. *Naïve*: Varying the Evolutionary Dynamics.

In Fig. 1 and Fig. 2, we see the percentage of simulations that result in cooperator dominance as we vary r and s. Across the majority of the parameter space, *Follow Flee* outperforms *Walk Away* in terms of promoting the evolution of cooperation. *Walk Away* has more success in spreading cooperation at lowest values of r and s, as across the remainder of the space it performs relatively poorly. *Walk Away* at best only achieves wide-spread cooperation in 50% of simulations for a very limited range of parameter values. On the other hand, *Follow Flee* dramatically improves upon its poor performance in very low parameter setting for r and s, and manages to almost completely counteract the influence of defectors. Additionally, we can identify that increasing the reproduction rate has a bigger impact on the outcome of a simulation than increasing the number of time steps per generation; both need to be considered in order to produce the best results for the evolution of cooperation.

4.3 Experiment 3: Varying the Density

In this experiment we investigate the influence of density on the outcome of a simulation separately with both the *Walk Away* and *Follow Flee* strategies. The parameters from the baseline experiment will be restored, except for the grid size which is varied. The values $L = \{15, 20, 25, 30, 35, 40, 45\}$ are investigated, while the population size N remains constant. In this way, we first consider the performance of both strategies in very high densities, and then consider environments with lower densities. A new set of simulations is run for each value of N with each strategy competing against the *Naïve* strategy.

Figure 3 illustrates the relationship between grid size and the percentage of simulations in which cooperation dominates for both the *Walk Away* and *Follow Flee* strategies. At high densities neither strategy is able to induce cooperation. At low densities both strategies can induce a practically complete adoption of cooperation. However, as the grid size grows we can see that *Follow Flee* capitalizes on the dilution of the grid much earlier, and more swiftly than *Walk Away*. *Follow Flee* is capable of promoting the dominance of cooperation in a greater percentage of simulations in harsher environments. While *Walk Away* does achieve similar results in low densities, it has already been shown [17] that cooperation is enhanced by highly mobile agents in these environments. Density has such a significant influence on the emergence of cooperation because it directly impacts the number of interactions cooperative agents have with defectors, and it determines the space with which agents can avoid unfavourable interactions.

4.4 Experiment 4: Walk Away vs. Follow Flee

In this experiment we attempt to directly compare both strategies. The *Naïve* strategy is removed as an option for players to keep the strategy proportions and population size constant, and to remove any additional complexities the presence of a third strategy may potentially introduce. As both *Walk Away* and *Follow Flee* are both mutually cooperative, we do not expect an evolutionary

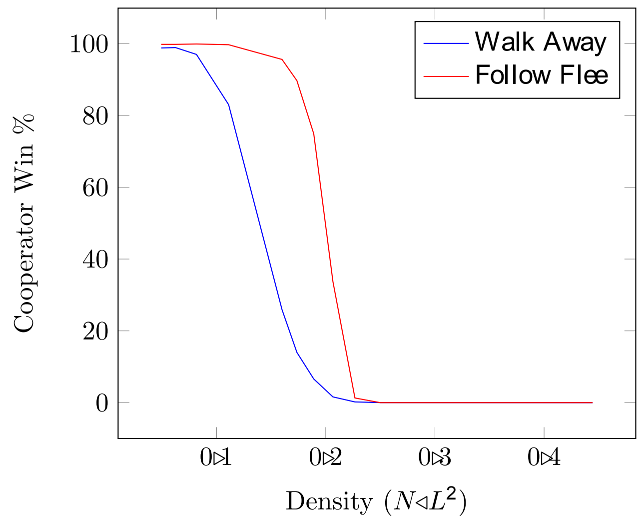

Figure 3: *Walk Away* vs. *Naïve* : Varying the Density

Table 4: Exp. 4 *Walk Away* vs. *Follow Flee* Results

Simulation Point	*Walk Away*	*Follow Flee*	Co-Existence
Defector Extinction	0%	10%	90%
End	10%	73%	17%

bias to favour either strategy once the defectors have died out. The population will be examined both at the end of the simulation and at the point at which defectors disappear. We record the percentage of simulations where the *Walk Away* strategy becomes dominant, where *Follow Flee* dominates, and the percentage of simulations where both strategies co-exist.

When *Walk Away* and *Follow Flee* compete in the same simulation, as one might expect, the defectors of both strategies are eliminated. In Tab. 4 we can see that in 90% of simulations, at the point at which defectors die out, neither strategy is dominant and both coexist within the population. However, in these scenarios where both strategies co-exist, the *Follow Flee* strategy outnumbers the *Walk Away* strategy four to one. Additionally, *Follow Flee* is dominant in the remaining 10% of simulations, and *Walk Away* is never fully dominant at the point defectors are eliminated. We also see that 73% of simulations end with the population adopting *Follow Flee*, only 10% of simulations result in the adoption of *Walk Away*, and the remaining 17% of simulations ending in a draw. This is despite the fact that there should be no selective bias between two mutually cooperative strategies. These results indicate a more substantial improvement of performance for *Follow Flee* than random fluctuation would permit.

5 Conclusion

In summary, we have presented *Follow Flee*, a contingent mobility strategy for playing the Spatial Prisoner's Dilemma, described the results of experiments designed to compare it to the noted *Walk Away* strategy, and in doing so demonstrated its superiority in promoting the evolution of cooperation. Both strategies were first independently tested and compared using a population of agents in a variety of evolutionary environments, including various density and reproductive settings, and then competed head-to-head in a single set of simulations. In every experiment conducted, *Walk Away* was outperformed by our *Follow Flee* strategy by significant margins; demonstrating that (1) *Follow Flee* is more resistant to the invasion of defectors, (2) it produces a greater percentage of cooperators victories in a wider range of evolutionary settings, (3) it is more successful in harsher density environments, and (4) can invade *Walk Away* agents despite the fact that both are mutually cooperative strategies.

We were unable to replicate the performance of *Walk Away* as demonstrated in Aktipis' paper [1]. Here, the traditional restriction of one agent per cell is relaxed, and the interaction radius of agents is reduced to those in the same cell. In addition, agents only participate in one 2-player game per turn, ignoring and oft-times excluding other agents from interactions. These incongruous environmental features, in combination with rules of the *Walk Away* strategy results in mutually cooperative pairings being unexpectedly difficult to break up or be exploited by defectors, giving cooperators a built-in advantage. We surmise that high levels of cooperation reported in this work may instead be credited to the environment implementation rather than the *Walk Away* strategy itself.

We attribute the success of *Follow Flee* to its highly mobile, proactive nature, and hypothesise that it is possible for it to make such significant gains due to its ability to generate and maintain cooperative clusters. As illustrated in Experiment 1, *Follow Flee* is capable of inducing the emergence of cooperation in a far greater percentage of simulations. The *Walk Away* cooperator pairs are immobile, which prevents them from actively seeking out new mutually cooperative interactions. The *Follow Flee* cooperators, on the other hand, are more likely to increase their number of mutually cooperative relationships, thus maintaining a higher average payoff, and so giving them an evolutionary edge. In contrast to the *Follow Flee* strategy, cooperators using *Walk Away* do not knowingly maintain these beneficial relationships when being pursued by defectors, and thus can more easily be broken up. Results indicate that the *Follow Flee* strategy can invade *Walk Away*, even though both strategies always cooperate.

The strengths of *Follow Flee* lie in its adaptability and simplicity. Previously, it has been stated that cooperation is enhanced in the presence of mobility [18, 19, 12], but only when those mobility rates were low or moderate. However, using *Follow Flee* we have managed to generate good levels of cooperation in this model's highly mobile and dynamic environment. We have constructed a promising contingent mobility strategy that is extremely successful at spreading cooperation throughout a mobile population without the need for complex computation, costly memories, or central control.

We have explored this contingent strategy in an abstract model. Future work will involve grounding these models in physically embodied agents using simple robots. We also wish to attempt to explore more realistic scenarios where simple contingent mobility strategies are witnessed in organisms that move towards fellow cooperators and move from defectors.

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