

Design of Influencing Agents for Flocking

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ABSTRACT

Flocking is a coordinated collective behavior that results from local sensing between individual agents who have a tendency to orient towards each other. Flocking is common amongst animal groups and could also be useful in robotic swarms. In the interest of learning how to control flocking behavior, several pieces of recent work in the multiagent systems literature have explored the use of influencing agents for guiding flocking agents to face a target direction. However, the existing work in this domain has focused on simulation settings of small areas with toroidal shapes. In such settings, agent density is high, so interactions are common, and flock formation occurs easily. In our work, we study new environments with lower agent density, wherein interactions are more rare. We study the efficacy of placement strategies and influencing agent behaviors drawn from the literature, and find that the behaviors that have been shown to work well in high-density conditions tend to be much less effective in the environments we introduce. The source of this ineffectiveness is a tendency of influencing agents explored in prior work to face directions intended for maximal influence that actually separate the influencing agents from the flock. We find that in low-density conditions maintaining a connection to the flock is more important than rushing to orient towards the desired direction.

We use these insights to propose new placement strategies and influencing agent behaviors that

overcome the difficulties posed by our new environments. The best influencing agents we identify act like normal members of the flock to achieve positions that allow for control, and then exert their influence. We dub this strategy “follow-then-influence.”

We also tackle this problem by using genetic programming to evolve ad hoc behaviors for influencing agents. We use a hand-constructed domain-specific language and evolve populations in a small test environment, before testing the best candidates in larger scenarios. We find that the genetic behaviors do well both in small-scale and large-scale simulations, a property that does not hold of the other hand-constructed behaviors [NEED TO RUN SIMULATIONS TO MAKE SURE THIS IS TRUE]. In particular, the genetic behaviors strike a balance between quickly turning their neighbors towards the goal direction while not losing influence by flying away from their neighbors.

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Introduction

0.1 FORMAT

FORMAT:

Introduce flocking, then introduce influencing agents. Talk about low-density vs. high-density, and briefly mention hand-crafted algorithms for dealing with low-density flocking. Finally, talk about using genetic algorithms for both.

0.2 BARBARA INTRO

Across nature, flocking behavior can be found in a variety of species, from flocks of birds, to herds of quadrupeds, schools of fish, or swarms of insects. In such species, groups exhibiting collective behavior emerge from simple, local rules²⁶. An open question is whether externally-controlled influencing agents can be used to affect the behavior of flocks.

Previous work^{8,9,10,13,12,11,7} has explored the use of influencing agents to guide flocking agents to face a target direction in small and toroidal settings. In such settings, agent density is high, so interactions are common, and flock formation is rapid. In this work, we focus on lower-density settings where interactions are rarer and flock formation is more difficult. We study how influencing agent priorities must change in these settings to be successful and propose new influencing agent strategies to adapt to the challenges posed by these settings.

Low-density settings are important to study because they capture dynamics in situations where flocking may not occur naturally, but where we might want to instigate flocking behavior; imagine a herd of buffalo that is currently grazing, or a spooked flock of birds where individual agents fail to coordinate. It may also have implications for coordination in low-density swarms of robotic multi-agent systems, where control may be imperfect, such as RoboBees². More broadly, flocking has implications for consensus in animal groups^{30,27,3} and in human social networks¹⁷; it has also been used to model multivariate timeseries and study human movement^{22,24}. In all these cases, agent density may vary greatly, so it is important to understand influencing agent dynamics in both low density and high density settings.

For our work, we draw heavily from a recent series of studies of this problem by Genter and Stone^{8,9,10,13,12,11,7}. Genter and Stone study influencing agent placement and behavior in small, toroidal environments.* In such environments, agents are bound to a small space and have unlimited opportunities to re-enter the screen and join a flock; flock formation is rapid.

We study this question in a more adverse environment by proposing two new test settings with lower agent density. In one setting, we keep the simulation space toroidal but increase the size of the space by several factors, greatly decreasing agent density. Flock formation is still provably guaranteed in this setting, but is much less rapid, so we study whether influencing agents can speed up flock formation. In the other setting, we make the simulation space non-toroidal but start the flocking agents in a circle in the center. Since this space is non-toroidal, flock formation is not guaranteed, so we study whether influencing agents can instigate flocking behavior by keeping the flocking agents in a pre-defined area, or move them all in a certain direction.

To help organize our analysis, we consider three different aspects of influencing agent design: placement strategy, local behaviors, and global behaviors. Placement strategies refer to the initial placement of influencing agents in the simulation space and their placement relative to flocking agents. Local behaviors dictate how an influencing agent attempts to influence local neighbors to face a given goal direction. Global behaviors, on the other hand, dictate how influencing agents determine their goal direction. For example, we might program all the influencing agents to have a pre-determined goal direction such as East or South, or we might program a global behavior that

*In a toroidal environment, agents that exit the simulation space from one side immediately re-appear on the other side

picks a goal direction after some time based on the initial dynamics of the simulation.

We find that in environments with low agent density, agent interactions are rare, so results from experiments in smaller settings do not translate well to larger settings. In particular, when agent interactions are rare, maintaining a connection to the flock becomes a key factor in the efficacy of influencing agent behaviors. As a result, simple local behaviors such as “face the goal direction” are often superior to more complex local behaviors that try to optimize for speed. We also experiment with a number of new strategies and find that a multi-stage approach of “follow-then-influence” can be effective in certain situations. In this approach, influencing agents start out by obeying the flocking rules, embedding themselves inside small, naturally-forming flocks. After some time, the influencing agents start influencing their neighbors to face a given goal direction. Finally, we find that reasonable placement strategies are often interchangeable, and that more complex strategies often perform similarly to random strategies.

The main contributions of this work are:

- An investigation of two new low-density flocking settings, where flock formation is more difficult.
- The introduction of new placement strategies and influencing agent behaviors to adapt to the difficulties presented by these new settings.
- Analysis of the major differences in influencing agent priorities in low-density vs. high-density settings.

The rest of this paper is organized as follows: §?? describes our formal flocking model and our new test settings. §?? describes the role of influencing agents and formalizes concepts of placement strategies and behaviors. §5.1 describes our experimental setup and the experiments we run to eval-

uate our placement strategies and behaviors in our test settings. We discuss the results and their implications in §???. In §??, we discuss related work and other approaches. Finally, we conclude and discuss future work in §??.

0.3 RADHIKA INTRO

Across nature, flocking behavior can be found in a variety of species, from flocks of birds, to herds of quadrupeds, schools of fish, or swarms of insects. In such species, groups exhibit collective behavior that emerges from simple, local rules²⁶. An open question is whether externally-controlled influencing agents can be used to affect the behavior of flocks. For example, environmental engineers might want to steer flocks of birds away from windmills, or steer a school of fish away from critical dam infrastructure.

Previous work in the literature has primarily studied hand constructed behaviors for such influencing agents. In this work, we aim to explore a wider range of the solution space using evolutionary algorithms to automatically generate and evaluate different influencing behaviors.

To start, we limit ourselves to purely ad hoc behaviors; influencing agents know of a goal direction ahead of time, but otherwise cannot co-ordinate with each other in any way. Instead, influencing agents must choose a direction simply based on the relative position and heading of their neighbors. This allows for direct comparisons to previous work by Genter and Stone, which proposed algorithms that operate under similar constraints^{8,9,10,13,12,11,7}.

In order to build behaviors that work with variable numbers of neighbors, we evolve programs that are applied iteratively to each neighbor using a functional programming construct called a fold.

In a fold, a function is applied in turn to each item in a list, updating an accumulator value for each one. The final value of the computation is the value of the accumulator after each item has been folded over.

In our work, we define a simple language that performs arithmetic computations on scalar values and angles, and evolve different functions to use in the fold. To make the evolutionary process fast enough, we first evaluate different functions in a small environment, with six neighbors that start in a circle around a single influencing agent. We run four trials; in each trial, the six neighbors (and the influencing agent) are facing one of the cardinal directions, and the target direction is east. We measure the average angle offset from the goal direction of the flocking agents after 100 steps and take the average across the four trials as the fitness value for the proposed program. We then run the evolutionary algorithm on this fitness value and mutate the best candidates each generation.

Next, we evaluate the candidates generated by the evolutionary algorithm against a larger setting drawn from the literature. To help organize this part of the analysis, we split influencing agent design into three different aspects: placement strategy, local behaviors, and global behaviors. Placement strategies refer to the initial placement of influencing agents in the simulation space and their placement relative to flocking agents. Local behaviors dictate how an influencing agent attempts to influence local neighbors to face a given goal direction. These are equivalent to the ad hoc behaviors that we are evolving, and we use our evolved ad hoc behaviors for this aspect of the broader analysis. Global behaviors, on the other hand, dictate how influencing agents determine their goal direction. For example, we might program all the influencing agents to have a pre-determined goal direction such as East or South, or we might program a global behavior that picks a goal direction after some

time based on the initial dynamics of the simulation.

We take placement strategies and global behaviors from previous literature and evaluate their efficacy in a larger test setting, also drawn from the literature. In this setting, proposed in previous work⁶, the agents start out in a 1000x1000 toroidal grid, and the simulation is run until half the agents converge to one direction. In this setting, agent density is low, so interactions are rare. However, flock formation is still provably guaranteed, so the metric of interest is how much faster the influencing agents can help the Reynolds-Viscek agents reach convergence. Previous work found that in low-density settings, it is important for agents to maintain influence over time; behaviors designed to quickly encourage convergence tended to turn influencing agents in directions that took them away from the flock.

We find that the genetic behaviors can both encourage faster convergence in the short term while still maintaining influence over the long-term. As a result, they can outperform the best hand-constructed algorithms in small simulation spaces while not falling to the common pitfalls of the larger simulation spaces. However, they can also be difficult to understand and reason about. In particular, some genetic behaviors work very well when paired with certain global behaviors, but experience catastrophic failures when paired with other global behaviors.

The main contributions of this work are:

- A functional language to define ad hoc influencing agent behaviors.
- An evolutionary algorithm to evolve and evaluate candidate programs in this language.
- Analysis of the efficacy of the programs evolved by this algorithm and their strengths and shortcomings relative to hand-constructed algorithms.

The rest of this paper is organized as follows: §?? discusses recent work in this area and how it relates to our work. §?? describes the formal flocking model and the role of influencing agents. §?? discusses our domain-specific language and evolutionary algorithm. §?? describes our experimental setup in more detail, and presents the results of our experiments. Finally, we conclude and discuss future work in §??.

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1

Background and Related Work

1.1 PREVIOUS WORK BY GENTER AND STONE

In this section, talk about previous work by Genter and Stone; discuss their settings and algorithms, and present some of their results.

1.2 OTHER RELATED WORK IN FLOCKING

Talk about all the other related work.

1.3 GENETIC PROGRAMMING

Talk about related work in GP

1.4 BARBARA RELATED WORK

Our work builds mainly upon the work of Genter and Stone, who have recently published a series of papers on the best way to influence an existing flock to change direction^{13,10,9,8,12,11}. This prior literature has studied a number of placement strategies and influencing agent behaviors, including questions of how best to join or leave a flock in real scenarios. Genter's PhD thesis also presents results from simulations with a slightly different implementation of Reynold's flocking model, as well as physical experiments with these algorithms in a small RoboCup setting. This prior literature has almost exclusively studied small environments, where density of agents is high, and quick flock formation is virtually guaranteed. In our work, we study two new low-density environments and introduce new placement strategies and influencing agent behaviors to adapt to the difficulties presented by these new environments.

Han et. al. have¹⁵ published a series of papers showing how to align a group of agents in the same direction. This literature has assumed a single influencing agent with infinite speed, and has used this property to construct a behavior that has the influencing agent fly around and correct the orien-

tation of agents one at a time. The result is that the Reynolds-Viscek agents all eventually converge to the target direction, but are not connected to each other. In our work, we limit the speed of influencing agents to be the same as the Reynolds-Viscek agents to prevent the use of behaviors like this, and in hopes that our results will be more applicable to real applications; we suspect that influencing agents that act similarly to real birds will be more successful in real-world applications.

Jadbadbaie et. al.¹⁶ have studied variations on the Reynolds flocking model from an analytical perspective, with no influencing agents. A strong result from this literature is that a group of Reynolds-Viscek agents in a toroidal setting will eventually converge regardless of initial conditions. However, there has been less analytical work on the speed of flock formation, and very little on the use of influencing agents to speed up flock formation or to force flocks to face given directions.

Su. et. al.²⁵ have also studied the question of flock formation and convergence, but have studied the question in the context of the Olfati-Saber flocking model²⁰. This model assumes the existence of a single virtual leader that non-influencing agents know about. The virtual leader plays the role of an influencer here, but has special control over the other agents based on its status. In our work, we assume that influencing agents do not have any special interaction rules with Reynolds-Viscek agents.

Couzin et. al.³ have studied this question with a slightly different formulation, and with a different model of flocking behavior. In their model, flocking behavior is achieved by maintaining distance between neighbors, and they cast the problem as one of informed individuals (analogous to influencing agents) trying to change the trajectory of the flock. The informed individuals are not externally-controlled; they simply have information about the “correct” orientation. In partic-

ular, the informed individuals can be wrong or have different opinions than other individuals, so information transfer is key. This differs from the settings we study, where influencing agents are completely autonomous and agree on a goal direction.

Other researchers have tackled this question with real flocking agents. Halloy et. al.¹⁴ have used robotic influencing agents to move cockroaches to areas they would otherwise avoid. Cockroaches display flocking behavior, but with very different models from the one that we study. In this case, Halloy et. al. have exploited the cockroaches’ inability to differentiate between real cockroaches and the robotic influencing agents.

Vaughan et. al.²⁸ have used robotic influencing agents to herd a flock of ducks (on the ground) to a goal position in a small caged area. The approach here largely uses the robot agents to “push” the ducks from a distance, like a dog herding sheep. The dynamics in this case are very different from the models we study; when the ducks are on the ground, they can stand still, for instance, and the fence limits the ducks’ behavior.

1.5 RADHIKA RELATED WORK

1.5.1 FLOCKING

Our work builds mainly upon the work of Genter and Stone, who have recently published a series of papers on the best way to influence an existing flock to change direction^{13,10,9,8,12,11}. This prior literature has studied a number of placement strategies and influencing agent behaviors, including questions of how best to join or leave a flock in real scenarios. Genter’s PhD thesis also presents re-

sults from simulations with a slightly different implementation of Reynold’s flocking model, as well as physical experiments with these algorithms in a small RoboCup setting. This prior literature has exclusively studied hand-constructed placement strategies and behaviors. In our work, we present first steps towards automating the design process by evolving local components of influencing agent behaviors.

We also draw from previous work that studied Genter and Stone’s algorithms in low-density settings and proposed new algorithms to deal with the issues introduced by low-density settings⁶. This previous work showed that, in low-density settings, maintaining influence was of paramount importance. In our work, we draw from the settings and behaviors presented in the previous work to conduct a full analysis of our genetic behaviors.

Han et. al. have¹⁵ published a series of papers showing how to align a group of agents in the same direction. This literature has assumed a single influencing agent with infinite speed, and has used this property to construct a behavior that has the influencing agent fly around and correct the orientation of agents one at a time. The result is that the Reynolds-Viscek agents all eventually converge to the target direction, but are not connected to each other. In our work, we limit the speed of influencing agents to be the same as the Reynolds-Viscek agents to prevent the use of behaviors like this, and in hopes that our results will be more applicable to real applications; we suspect that influencing agents that act similarly to real birds will be more successful in real-world applications. Furthermore, we limit our genetic behaviors to only consider stimuli in an influencing agent’s neighborhood. However, we are hopeful that, with more work, genetic programming techniques can help develop behaviors for models that work under different situations and assumptions.

Jadbadbaie et. al.¹⁶ have studied variations on the Reynolds flocking model from an analytical perspective, with no influencing agents. A strong result from this literature is that a group of Reynolds-Viscek agents in a toroidal setting will eventually converge regardless of initial conditions. However, there has been less analytical work on the speed of flock formation, and very little on the use of influencing agents to speed up flock formation or to force flocks to face given directions.

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1.5.2 GENETIC PROGRAMMING

We are not the first researchers to apply genetic algorithms to the domain of controlling agents in swarms; Dorigo and Trianni used genetic algorithms to evolve controllers for s-bots, swarming robots designed to self-assemble and move together as a swarm-bot⁵. However the problem solved in that research is not the same as the problem we attempt to solve. In the swarm-bot project, the evolved controllers ran cooperatively on every agent in the swarm, whereas our controllers only run on a minority of the agents yet still need to influence the collective behavior of the swarm. Another key difference is that Dorigo and Trianni used a neural network connecting the sensors to the actuators of their robots as their genome, whereas we draw on the genetic programming literature to evolve controlling programs that are able to handle varying amounts of input data and display arbitrarily complex behaviors.

Another use of genetic algorithms for developing controllers was when Sean Luke used genetic

programming to build a team for the RoboCup97 competition¹⁸. Like us, Luke used genetic programming with a domain specific language designed based on domain intuition, however his language had many more primitives than ours because the virtual soccer players he was evolving were capable of much more complex behaviors than our flocking agents. The execution model used by the RoboCup players was designed to simplify the work to be done by the evolved program without unnecessarily biasing it toward any particular strategy. We have similar goals when designing our own execution model and language.

Much work has been done on developing techniques for evolving programs in richer languages with complex constraints on which programs are valid¹. Although we use functional programming ideas in our execution model, we keep our language simple, with only conditional expressions for control flow structures and only a single type. Exploring a richer language with a type system to reduce the number of useless programs our genetic algorithm searches would be very interesting, but we leave it as future work.

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2

Problem Description

2.1 FLOCKING MODEL

Like other studies in the literature, we use a simplified version of Reynold's Boid algorithm²¹ to model the flock. In this simplified model, also proposed independently by Vicsek and collaborators²⁹, agents change their alignment at every step to be similar to the average alignment of other agents in their neighborhood. At each time step, each agent a_i moves with constant speed $s = 0.7$,

has orientation $\vartheta_i(t)$, and position $p_i(t) = (x_i(t), y_i(t))$. At timestep t , a_i updates its position based on its alignment: $x_i(t) = x_i(t-1) + s \cos(\vartheta_i(t))$ and $y_i(t) = y_i(t-1) - s \sin(\vartheta_i(t))$. At the same time, the agents change their orientation based on the alignments of neighboring agents. Let the neighbors $N_i(t)$ be the set of agents at time t that are within neighborhood radius r of a_i , not including a_i itself. At timestep t , each agent updates its orientation to be the average of their neighbors' orientations:

$$\vartheta_i(t+1) = \vartheta_i(t) + \frac{1}{|N_i(t)|} \sum_{a_j \in N_i(t)} \text{calcDiff}(\vartheta_j(t), \vartheta_i(t)),$$

where calcDiff computes the difference between two angles, always returning an angle between 0 and π .

2.2 INFLUENCING AGENTS

Should probably describe influencing agents and their limitations at a high level here; look at introduction of the influencing agents section from Barbara paper, or the influencing agents subsection from the Radhika paper

2.3 NEW SETTINGS

Previous work has studied influencing agents in a small toroidal 150×150 grid, with neighborhood radius $r = 20$ ^{12,II}. In this work, we study low-density dynamics by introducing two new settings that are more adverse to flock formation; we call these new settings the *large* setting and the *herd* setting.

In both these settings, we set the neighborhood radius to $r = 10$.

In the *large* setting, non-influencing agents are randomly placed in a toroidal 1000×1000 grid with random initial orientations. The larger grid size results in lower agent density; as a result, agents start out much farther away from other agents' neighborhoods, and interactions are much rarer. However, since the simulation space remains toroidal, convergence to a single flock is still provably guaranteed, so we are primarily interested in studying the length of time to convergence in this case [CITE THIS]. In the *herd* setting, non-influencing agents are placed randomly in a circle of radius 500 whose origin lies at the center of a 5000×5000 non-toroidal grid. When agents reach the edge of the grid, they simply keep going; in this way, agents can get "lost" from the rest of the flock. As a result, convergence to a single flock is not guaranteed [CITE THIS]. Therefore, we are interested in studying how well influencing agents can keep the non-influencing agents from getting lost.

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3

Algorithms for Influencing Agents

3.1 PLACEMENT STRATEGIES (BARBARA PAPER)

In this work, we study a number of different placement strategies, shown in Figure 3.1. Except for slight modifications to make some of these strategies circular, all the strategies are drawn from the literature^{13,7}. We note that the question of how to maneuver influencing agents to reach the positions given by these placement strategies is important, but out of scope for this paper. For a discussion of

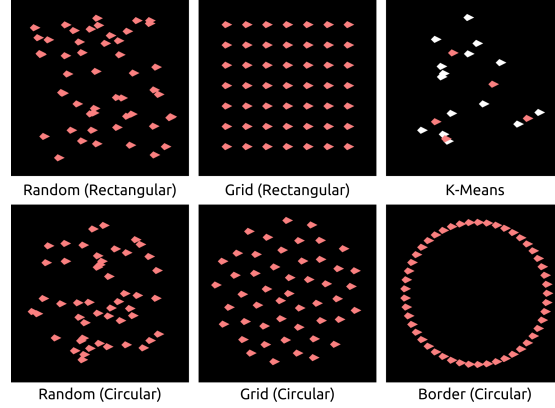


Figure 3.1: The different placement strategies we explore in this paper. Red agents are influencing agents, and white agents are Reynolds-Viscek agents. Note that k-means is the only placement strategy where the placement of influencing agents depends on placement of Reynolds-Viscek agents.

this question, we refer the reader to Genter and Stone^{12,7}.

For the *large* setting, we study three placement strategies: *random*, *grid*, and *k-means*. The random placement strategy, as its name suggests, places influencing agents randomly throughout the grid. The grid placement strategy computes a square lattice on the grid and places influencing agents on the lattice points. This strategy ensures regular placement of influencing agents throughout the grid. The k-means placement strategy uses a k-means clustering algorithm on the positions of Reynolds-Viscek agents in the simulation space. This strategy finds a cluster for each influencing agent by setting k equal to the number of influencing agents, and then places an influencing agent at the center of each cluster.

We develop similar placement strategies for our herd setting, with some differences. To adapt the strategies to a circular arrangement of agents, we define each strategy in terms of some radius r about an origin O , except for the *k-means* strategy, which remains the same. We modify the *random*

placement strategy to randomly distribute agents within the circle of radius r about the origin O , instead of the entire simulation space. We adapt the grid placement strategy to a circular setting using a sunflower spiral²³. In polar coordinates relative to O , the position of the n -th influencing agent in a sunflower spiral is given by $(c\sqrt{n}, \frac{2}{\varphi}n)$, where φ is the golden ratio, and c is a normalizing constant such that the last influencing agent has distance r from O . We also introduce a circle border placement strategy, inspired from the border strategies from¹³. This strategy places agents on the circumference of the circle of radius r around the origin O . We refer to the circular strategies as *circle-random*, *circle-grid*, and *circle-border*, respectively.

3.2 BEHAVIORS (BARBARA PAPER)

NOTE: POSSIBLY GET RID OF GLOBAL/LOCAL DISTINCTION?

MENTION THAT WE INTRODUCE HAND-CONSTRUCTED BEHAVIORS HERE

ALSO ADD NEW BEHAVIORS THAT WE STUDY FOR THESIS

NOTE: UPDATE WHEN CAMERA-READY VERSION OF BARBARA PAPER IS DONE

Once we have placed our influencing agents, we still need to design how they will work together to influence the flock. We call this aspect of the design influencing agent behaviors. In the present work we focus on decentralized “ad-hoc” algorithms for our influencing agents since this class of algorithms has been the focus of the existing multiagent systems literature on this topic^{7,10,11}.

To help organize our analysis, we split behaviors into local and global components; each influencing agent behavior is composed of a local and global component. The local component takes a desired orientation as an argument and dictates which direction an influencing agent will face to

try to influence its neighbors towards the goal orientation. The global component, on the other hand, dictates the desired orientation to feed to the local component and how the influencing agents might coordinate to decide on a desired orientation. For example, one behavior might be for the influencing agents to circle around the center of a grid and get the Reynolds-Viscek agents to circle with them. The global component would compute the desired orientation necessary at each step to maintain the circling behavior, and the local component would compute which exact direction to face to get the Reynolds-Viscek agents to face the desired orientation at that step. For grammatical sanity, we will refer to different candidates for local and global components as “local behaviors” and “global behaviors” throughout the rest of this paper; however, it is important to recognize that any actual behavior must have a local and global component.

LOCAL BEHAVIORS

Like our placement strategies, we draw on Genter and Stone for many of our local behaviors^{11,12,13}. In previous work, they have introduced baseline behaviors *face* and *offset momentum*, as well as more sophisticated behaviors *one step lookahead* and *coordinated*. Each of these behaviors requires a goal angle ϑ^* . In *face*, influencing agents always face the angle ϑ^* . In *offset momentum*, influencing agents calculate the average velocity vector of the agents in their neighborhood, and take on a velocity vector that, when added to the average velocity vector, sums to the vector pointing in direction ϑ^* . In *one step lookahead*, each influencing agent cycles through different angles and simulates one step of each of its neighbors if it were to move in that angle. It adopts the angle that results in the smallest average difference in angle from ϑ^* among all its neighbors. Finally, in *coordinated*, each agent

Table 3.1: Summary of global behaviors we investigate

Setting	Type	Name	Description
Large		<i>Direct</i>	Influence neighbors or face goal
		<i>Random</i>	Influence neighbors or face random
		<i>Multistep</i>	<i>Follow-then-influence</i>
Herd	Net	<i>Direct</i>	Influence neighbors or face goal
	Stationary	<i>Circle</i>	Trace circle around agents
		<i>Polygon</i>	Trace polygon around agents
		<i>Multicircle</i>	<i>Follow-then-influence</i>

pairs with another and runs a one step lookahead to minimize the average difference in angle from ϑ^* among both their neighbors. For a more detailed explanation of these behaviors, especially the *coordinated* behavior, we direct the reader to Genter and Stone¹¹.

GLOBAL BEHAVIORS

The global behaviors we investigate are listed in Table 3.1. We have three global behaviors for the *large* setting: *direct*, *random*, and *multistep*. As its name suggests, the *direct* global behavior has each influencing agent use a local behavior to directly influence its neighbors towards the goal angle ϑ^* . When an influencing agent has no neighbors, it simply faces the goal direction.

The *random* global behavior is very similar, but it directs influencing agents in a random direction when they have no Reynolds-Viscek neighbors. We introduced this behavior as a response to interactions where an influencing agent is almost successful in changing the direction of a group of Reynolds-Viscek agents, but gets separated before it is completely successful. In these cases, the Reynolds-Viscek agents are left on a trajectory that is almost parallel to the goal direction; as a result, further interactions with influencing agents are rare.

The *multistep* behavior is a novel contribution and adopts what we call a “follow-then-influence”

behavior. In the initial stage, influencing agents simply behave like normal Reynolds-Viscek agents; as a result, they easily join flocks and become distributed throughout the grid. At the same time, the influencing agents perform a global calculation of the total number of Reynolds-Viscek agents that are path-connected to influencing agents. Here, we define two agents as being path-connected if there is a path between them, where edges are created by two agents being in each other's neighborhood. Once that number passes some threshold T , the influencing agents calculate the average angle $\bar{\vartheta}$ among all the agents that are locally connected to influencing agents, and from there adopt the *direct* behavior with goal $\bar{\vartheta}$. We choose $\bar{\vartheta}$ to minimize the amount that each influencing agent needs to turn its flock on average. MENTION GLOBAL VIEW HERE AND THE SMALLER VERSION

For the *herd* setting, we divide our global behaviors into two categories: a *net* behavior, and a set of *stationary* behaviors. As a reminder, in the *herd* setting, the simulation space is non-toroidal, and all the Reynolds-Viscek agents start in a circle in the center. In this setting, flock formation is not guaranteed, so we are interested in using influencing agents to instigate flocking behavior. There are two different choices we can make; we can either try to force the Reynolds-Viscek agents to stay in the center (*stationary* behaviors), or we can let the influencing agents direct the Reynolds-Viscek agents away from their initial starting position. Since all our agents have a constant speed, the former is much more difficult than the latter, so we must evaluate them separately.

The *net* behavior is equivalent to the *direct* behavior; there is a single pre-determined goal direction, and the influencing agents try to direct the Reynolds-Viscek agents towards the goal direction. We call it a net behavior because it looks as if the influencing agents are “catching” the Reynolds-Viscek agents in a net.

We study three *stationary* behaviors: *circle*, *polygon*, and *multicircle*. The *circle* and *polygon* behaviors have each influencing agent trace a circle or polygon around the origin. For placement strategies where influencing agents have different distances to the origin, the influencing agents simply trace circles and polygons of different radii.

The *multicircle* behavior is analogous to the *multistep* behavior from *large*. The influencing agents start out by circling around the origin and wait for Reynolds-Viscek agents to enter their neighborhood. Once they detect Reynolds-Viscek agents in their neighborhood, they adopt a “following” behavior where they act like Reynolds-Viscek agents to integrate into a small flock. They continue this following stage until reaching a final radius r_F , at which point they again adopt a circling behavior. In addition to building influence by following before influencing, this behavior also makes maintaining influence easier; since the final radius is larger than the original radius, the final path turns less sharply than if the influencing agents had stayed at their original radius. To the best of our knowledge, this is the first presentation of such a multi-stage behavior to induce circling behavior under the Reynolds-Vicsek model in the literature.

Besides the above global behaviors, we also explored a few more variations on the *net* behavior and the *multicircle* behavior. One variation of the *net* behavior was equivalent to the *random* global behavior from the *large* setting. The other was similar to the stationary *circle* behavior; influencing agents would trace a circle until encountering Reynolds-Viscek agents, whereupon they would influence the Reynolds-Viscek agents towards the goal direction. The variations on the *multicircle* behavior included different final radii from those presented in §??, as well as a variation that introduced a transitional period between the initial following state and the final circling state. These additional

variants added few qualitative insights, so we do not report them for simplicity of exposition.

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4

Evolving (Local) Behaviors

To evolve local behaviors, we run genetic algorithms over genomes containing abstract syntax trees for a simple domain specific language we designed specifically for computing a new heading from a list of neighboring agents.

4.1 DOMAIN SPECIFIC LANGUAGE

All evolved local behaviors need to be well-defined for any number of neighboring agents, so we choose an execution model that generalizes over the number of neighbors a influencing agent has. Every expression in our domain specific language defines a function from an accumulator value representing a heading and a neighbor agent to a new accumulator value. Starting with an initial accumulator value, the same function is applied to each of the influencing agent's neighbors in decreasing order of distance. The result of each application becomes the accumulator value fed to the next application, and the result of the final application is the heading the influencing agent will take in the next time step. In functional programming terms, we are evolving a function used to fold over a list of neighbors. The pseudocode for this fold is in listing 4.1.

```
acc = initial_acc  
  
for neighbor in neighbors:  
    acc = f(acc, neighbor)  
  
return acc
```

Listing 4.1: A fold

The order in which neighbors are evaluated is meaningful, since the evolved functions are not necessarily commutative. We choose to evaluate them in decreasing order of distance to ensure that the results of programs that do not use the accumulator value are determined by the nearest neighbor of the influencing agent. If the influencing agent has no neighbors, its calculated heading

is equal to its initial accumulator value. A genome is comprised of an abstract syntax tree for the folding function and the initial accumulator value. The initial accumulator value is either the influencing agent's current heading or the goal direction, decided at random when an initial genome is created. An example of a hand-crafted genome is given in listing 4.2.

```
acc = current ;  
  
(add acc (mul influence heading))
```

Listing 4.2: A small genome that sets the agent's heading to the average of its neighbors' headings

By using a fold as our execution model, we can keep the syntax of the language very simple. Because the execution model handles looping over the list of neighbors, there is no need for the language itself to have syntax expressing loops or lists. Although allowing the language to have lists and loops would increase its expressiveness, we opted to keep the language simple while still expressive enough to allow the genetic algorithm to develop complex behaviors. We also chose to leave out other possible capabilities such as mechanisms for storing state other than the accumulator value and communicating with other influencing agents.

The expressions that make up the domain specific language are given in table 4.1. When evaluated, every expression in the language has a value in the range $[-1, 1]$, which is interpreted as an angle (in radians) by multiplying by π . All angles are relative to the influencing agent's current heading. Addition, subtraction, sine, and cosine operators treat their arguments as angles, but multiplication, exponentiation, arcsine, and arccosine treat them as scalar values. Division is purposefully excluded from the language because there is no meaningful way to enforce that its result is in the range $[-1, 1]$.

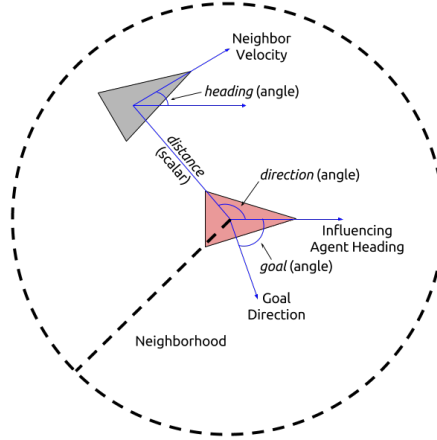


Figure 4.1: Some of the variables used in the domain-specific language.

Exponentiation is modified such that the exponent is implicitly shifted into the range $[0, 2]$ to enforce the same invariant.

We determined what information should be made available about neighboring agents by drawing on our own intuition about what information would be valuable in designing an influencing behavior, then transforming it to be in the range $[-1, 1]$. For example, knowing the index of the current neighbor allows for creating a function that gives more weight to closer neighbors (those with higher indices); knowing the distance to the current neighbor combined with the conditional expression, `gez`, allows for creating programs that ignore neighbors that are too close or too far away; and the product of the influence variable and some other value can be added to the accumulator to calculate an average over all neighbors. Figure 4.1 shows how the direction, distance, heading, and goal variables relate to the position of a neighboring agent.

To keep the language simple, angular and scalar values are used interchangeably. Introducing a type system to keep them separate would greatly reduce the space of programs the genetic algorithm

Expression	Semantics
direction	angle toward neighbor
distance	distance to neighbor / sensing radius
heading	relative heading of neighbor
influence	$1 / \#$ of neighbors
index	index of neighbor / $\#$ of neighbors
goal	angle toward goal direction
acc	the accumulator value
f	some constant $f \in [-1, 1]$
$(\sin e)$	$\sin(e \cdot \pi)$
$(\cos e)$	$\cos(e \cdot \pi)$
$(\text{asin } e)$	$2 \cdot \text{asin}(e) / \pi$
$(\text{acos } e)$	$2 \cdot \text{acos}(e) / \pi - 1$
$(\text{add } e_1 e_2)$	$\text{wrap}_{[-1,1]}(e_1 + e_2)$
$(\text{sub } e_1 e_2)$	$\text{wrap}_{[-1,1]}(e_1 - e_2)$
$(\text{mul } e_1 e_2)$	$e_1 \cdot e_2$
$(\text{exp } e_1 e_2)$	$e_1^{e_2+1}$
$(\text{gez } e_1 e_2 e_3)$	if $e_1 \geq 0$ then e_2 else e_3

Table 4.1: Language expressions

has to search through, at the expense of complicating the genetic operators, which would have to respect such a type system. We leave implementing such a type system as well as implementing a richer language as future work.

4.2 EVOLUTIONARY ALGORITHM

The two genetic operators we use in our genetic algorithm are the classic operators in genetic programming, crossover and mutation⁴. Crossover works by picking a random subtree from each of two abstract syntax trees and swapping them. Mutation picks a node at random from an abstract syntax tree and changes it into some new node, picked uniformly at random from the set of expres-

sion types available in the language. The children of the old node are made children of the new node in random order, although children may be lost if the new node has fewer children than the old node and new children may need to be randomly generated if the new node has more than the old node.

We start by randomly generating each member of the population. We evaluate each member with 6 Reynolds-Viscek agents in a small test setting, calculating the average absolute difference in angle of the Reynolds-Viscek agents from the goal direction after 100 steps. This gives a positive fitness value that we wish to optimize towards zero. In each generation, we choose the top N genomes to use as a seed population for the next generation, where N is a hyperparameter set by the user. We add those N genomes into the new population. Then, while the size of the new population is smaller than the size of the old population, we repeat the following:

1. Flip a coin to decide whether to create a new member(s) by mutation or crossover.
2. If mutation, randomly select one genome from the seed population, mutate it, and add it to the new population.
3. If crossover, randomly select two genomes from the seed population, and use them to perform crossover. This creates two new offspring; add them both if there is room, otherwise randomly select one to add.

We experimented with a few variations on this algorithm over the course of the project. We started by choosing one individual in each generation to mutate, and randomly replaced one individual, chosen proportionally to fitness (keeping in mind that closer to 0 is better). However, it was difficult for this algorithm to favor better candidates, since fitness values were so close to each other. We tried switching to a rank-proportional replacement algorithm, but this approach had the oppo-

site problem of distinguishing too finely between genomes with very similar fitness. We ultimately settled on our seed population approach as a compromise between these two forces. We also initially evolved genomes without the bias towards shorter genomes, but we found that this led to blow-out as soon as we added crossover.

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5

Experiments

5.1 BARBARA EXPERIMENTS

We extended the MASON simulator to run our experiments.¹⁹ We used the default parameters for the Flocking simulation that is included with the MASON simulator, except without any randomness, cohesion, avoidance, or dead agents. We sampled all metrics every 100 time steps and ran all experiments for 100 trials.

5.1.1 NO INFLUENCING AGENTS

Previous literature compared new influencing agent behaviors with baseline influencing agent behaviors, but did not compare to settings with no influencing agents. In order to observe the marginal contribution of influencing agents in future experiments, we start our investigation of the *large* and *herd* settings by studying flock formation in those environments without any influencing agents. We use two metrics to evaluate flock formation: average number of flocks formed and average proportion of lone agents at each time step.

In the *large* setting, we test on a 1000×1000 grid and vary the number N of Reynolds-Viscek agents from 50 to 300 in increments of 50. We run these simulations for 6000 time steps. In the *herd* setting, we use a 5000×5000 grid, position the herd in the center of the grid with radius 500, and vary N from 50 to 300 in increments of 50. We run these simulations for 6000 time steps.

5.1.2 INFLUENCING AGENTS IN THE LARGE SETTING

Next, we evaluate the contributions of influencing agents. To evaluate the contributions of influencing agents in the *large* setting, we measure the time required for half of the Reynolds-Viscek agents to face the same direction. Unlike in previous work, which has limited the goal direction to a single pre-determined goal direction, here we open up the possibility to convergence to any direction to match the goal of our multi-step behavior.

We test the *random*, *grid*, and *k-means* placement strategies, along with global behaviors *face*, *random*, and *multistep*, each paired with local behaviors *fact*, *offset momentum*, *one step lookahead*,

and *coordinated*. We place 300 Reynolds-Viscek agents on a 1000x1000 grid, with 300 Reynolds-Viscek agents and vary the number of influencing agents from 10 to 100 in intervals of 10.

5.1.3 INFLUENCING AGENTS IN THE HERD SETTING

To evaluate the contributions of influencing agents in the *herd* setting we measure a slightly different metric. Since we have two qualitatively different categories of global behaviors (net behaviors vs. stationary behaviors), the number of agents facing the same direction is irrelevant, since the stationary behaviors rotate the agents around the origin (in fact, if the Reynolds-Viscek agents are all facing the same goal direction, the stationary behavior has failed). Instead, we measure the number of Reynolds-Viscek agents that are connected to influencing agents at 15000 time steps; at this point in time, all the agents have travelled out of the grid, and no new interactions occur. As a result, this is a measure of sustained influence over the Reynolds-Viscek agents over time.

We examine the three circular placement strategies, *circle-border*, *circle-random*, and *circle-grid*, with two placement radii, 500 and 750, along with the *k-means* placement strategy. We split our examination of global behaviors between the *net* behavior (analogous to *face*) and three stationary behaviors - namely *circle*, *polygon*, and *multicircle*. We use a polygon with ten sides (a decagon) for our *polygon* experiments, and we vary the final radius for multicircle based on the initial placement radius. When the placement radius is 500, we set the final radius to 900; when the placement radius is 750, we set the final radius to 1100. Finally, we pair the *face*, *offset momentum*, *one step lookahead*, and *coordinated* local behaviors with all the global behaviors and placement strategies. We place 300 Reynolds-Viscek agents inside a circle of radius 500 at the center of a 5000x5000 grid, varying the

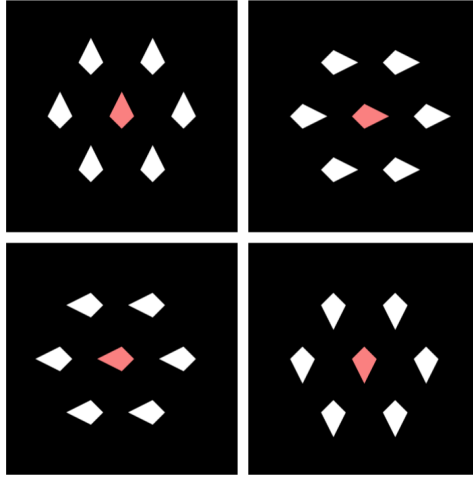


Figure 5.1: The four starting positions we use to evaluate genomes during evolution. We run the simulation for 100 steps and calculate the average angle offset from the goal direction across the six Reynolds-Viscek agents. The goal direction is east.

number of influencing agents from 10 to 100 in intervals of 10.

5.2 RADHIKA EXPERIMENTS

NOTE: IN RADHIKA PAPER, EXPERIMENTS AND RESULTS WERE PRESENTED AT THE SAME TIME

5.2.1 EVOLUTIONARY EXPERIMENTS

Each trial of one of the large-scale experiments takes dozens of seconds to run. Furthermore, the random placement of the Reynolds-Viscek agents creates high variability across multiple trials. Consequently, using large-scale experiments to evaluate genomes during evolution is infeasible. Instead, we evaluate the genomes on a set of four small experiments, shown in Figure 5.1. In each of these experiments, the influencing agent is placed in the center of six Reynolds-Viscek agents, each of which

is at the edge of the influencing agent’s neighborhood. All agents are initialized to face one of the cardinal directions, and we run the simulation for 100 steps. At the end, we measure the average absolute angle difference, in degrees, from the goal direction (east) across all six Reynolds-Viscek agents. Lower values are better. Initially, we evaluated genomes during evolution by randomly placing Reynolds-Viscek agents in a circle around the influencing agent. However, random placement resulted in high variability for the same genome between generations, and it became difficult for the algorithm to find better genomes. We ultimately settled on a deterministic test to both reduce this variability and to allow for memoization to make our algorithm run faster.

Finally, we add a small penalty for the number of nodes in the genome. This gives the following cost function:

$$\sum_{i=1}^6 \text{calcDiff}(\mathfrak{g}_i, \mathfrak{g}_{east}) + \alpha N_{nodes},$$

where N_{nodes} is the number of nodes in the genome, and α is a regularization factor. In our experiments, we set $\alpha = 0.1$ to allow development of complexity but to prevent blow-out.

5.3 GENTER AND STONE EXPERIMENTS

NEED TO PRESENT RESULTS FROM GENTER AND STONE EXPERIMENTS TOO

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6

Results

6.1 BARBARA RESULTS

6.1.1 NO INFLUENCING AGENTS

First, we briefly characterize the flocking behavior of a group of Reynolds-Viscek agents without influencing agents in the *large* and *herd* settings. We measure the number of clusters of agents that are path-connected and facing the same direction; each of these clusters forms a small flock. We also

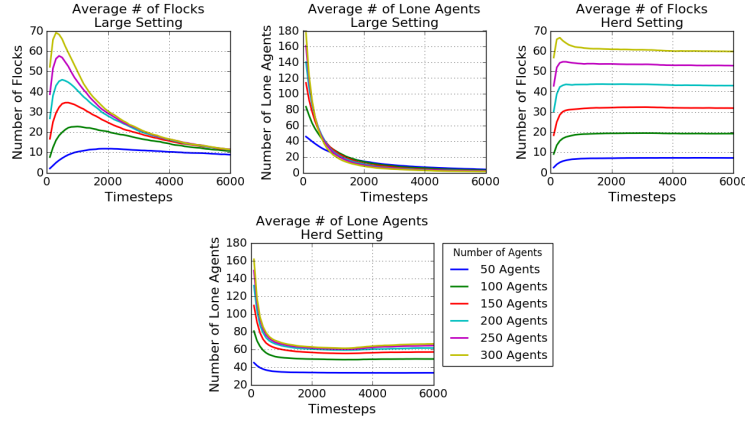


Figure 6.1: Average flock counts and lone agent counts over time for the *large* and *herd* settings with no influencing agents, varying the number of Reynolds-Viscek agents.

measure the number of lone agents (the number of agents with no neighbors). Figure 6.1 shows graphs of these values over time for our two settings.

In the *large* setting, there are two qualitative stages of convergence: initial flock formation and flock unification. In the first stage, individual agents collide with each other and form small flocks. In the second stage, these small flocks that formed collide with one another and join together to form larger flocks. In Figure 6.1, the first stage is represented by the initial increase in the average number of flocks, and the second stage is represented by the following decrease in the average number of flocks. This behavior is reflected in the continually decreasing number of lone agents; since the number of lone agents continues to decrease over time, we know that the decrease in the total number of flocks is due to flock convergence. Note that when there are more total agents, the absolute number of lone agents decreases faster and reaches a similar value to the other cases by the end of the simulation. In other words, the *ratio* of lone agents to total agents hits a lower value when there are more agents, but the final absolute number of total lone agents is still similar to the other

cases.

The two stages of convergence also occur somewhat in the *herd* setting, but the second stage is cut off by the non-toroidal nature of the setup. As flocks leave the starting area, the chances of interacting with other flocks vastly decreases, so most of the flocks formed from the first stage never end up merging with other flocks. This is reflected in the plateaus of both the total number of flocks and the total number of lone agents. Some small artifacts in the graphs are worth mentioning; since the agents start off in a much smaller area than in the *large* setting, many of the agents start out with a non-zero number of neighbors. This causes the initial value of the average number of flocks to be non-zero, and the average number of lone agents to be less than the total number of agents.

6.1.2 INFLUENCING AGENTS IN THE LARGE SETTING

Next, we study the efficacy of various behaviors and placement strategies in the *large* setting. The average times for 50% convergence under different combinations of placement strategies with global and local behaviors are shown in Figure 6.2. We show graphs for 50 influencing agents only, since the trends for the other numbers of influencing agents were similar (the major difference being that when there are more influencing agents, convergence happens faster). Note that smaller is better in these graphs. The most immediately striking finding is that, in our more adverse setting, the *one step lookahead* and *coordinated* local behaviors significantly underperform the *face* behavior irrespective of global behavior and also underperform *offset momentum* for the *face* and *random* global behaviors. This is an opposite result from Genter and Stone’s findings on smaller simulation spaces^{11,7}, which found that *one step lookahead* and *coordinated* outperform *face* and *offset momentum* (the latter of

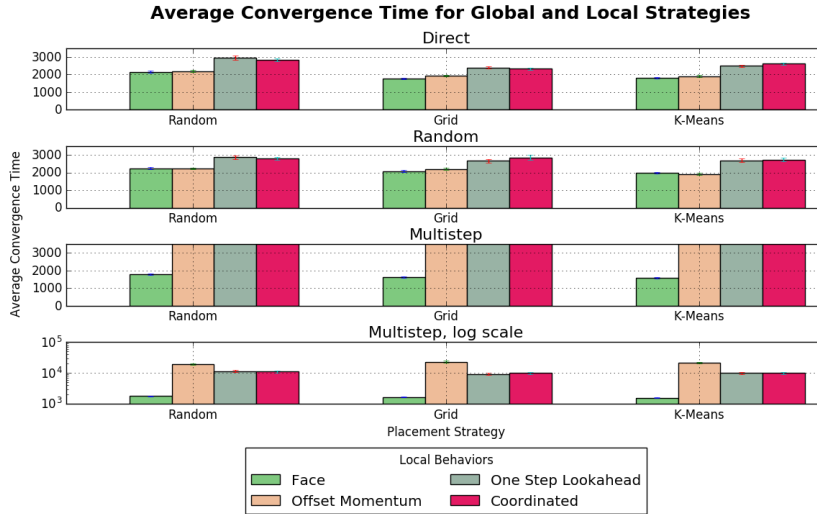


Figure 6.2: Average times to 50% convergence for 300 Reynolds-Viscek agents with 50 influencing agents in the *large* setting under different placement strategies, paired with various global and local behaviors. Smaller is better.

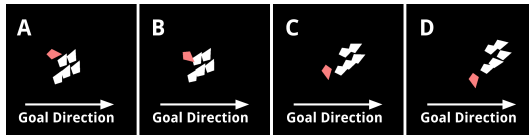


Figure 6.3: An example of an influencing agent losing influence under the *one step lookahead* behavior. The influencing agent is shown in red, and the Reynolds-Viscek agents are shown in white. In A, the influencing agent first encounters the flock of Reynolds-Viscek agents. In B-D, the influencing agent takes on directions that are oriented away from the goal direction to try to rapidly influence the Reynolds-Viscek agents, but the influencing agent has started to travel away from the flock by D.

which are in fact presented as “baseline” behaviors). This finding is also rather counterintuitive; why should the “smarter” behaviors underperform the simpler behaviors?

The answer is that, when agent interactions are rare, it is more important for influencing agents to *maintain influence* than it is for them to quickly change the direction of neighboring Reynolds-Viscek agents. The *one step lookahead* and *coordinated* behaviors underperform here because they tend to send influencing agents away from neighboring agents. An example of this phenomenon is

shown in Figure 6.3. The influencing agent, shown in black, adopts an orientation that turns neighboring Reynolds-Viscek agents towards the goal direction. Even though this does turn Reynolds-Viscek agents towards the goal direction, it cannot successfully turn all the agents in a single step; as a result, it must maintain that orientation for future steps. However, as long as the neighboring agents are not facing the goal direction, the influencing agent's chosen orientation takes it away from the center of the flock of Reynolds-Viscek agents, causing it to lose influence. Once the influencing agent has lost influence, it is difficult to catch up to the same flock, since influencing agents travel at the same speed* as Reynolds-Viscek agents. As a result, the influencing agent is not actively influencing the direction of any Reynolds-Viscek agents until it encounters another group of Reynolds-Viscek agents.

Note that this effect also happens on a smaller simulation space, but it is not nearly as pronounced; when interactions are very frequent, influencing agents that have lost influence can find another group of Reynolds-Viscek agents very quickly. As a result, the gains from the smarter local algorithm still outweigh the negative effects from losing influence.

This effect is more pronounced for the *multistep* behaviors. First, we note that the *multistep* global behavior paired with the *face* local behavior seems to slightly outperform the *direct* and *random* global behaviors, but the *multistep* global behavior paired with the other local behaviors drastically underperform anything else. What is the root cause of this difference? The *multistep* global

* There are some approaches which remove this speed constraint from influencing agents¹⁵. However, this allows for unrealistic behaviors wherein influencing agents travel to one Reynolds-Viscek agent and a time and change the direction of the individual Reynolds-Viscek agent before moving on to the next one. This results in Reynolds-Viscek agents that are all facing the same direction, but that are often not path-connected.

behavior starts out by creating many local flocks, some of which have influencing agents in them. When interactions are rare, the *offset momentum*, *one step lookahead*, and *coordinated* behaviors have difficulties changing the orientation of existing flocks quickly before losing influence. As a result, the *multistep* behavior takes an order of magnitude longer to reach convergence when paired with the other local behaviors.

Finally, we note that the effect of placement behaviors on convergence time are almost non-existent. When the density is lower, there is a much smaller chance that any influencing agent will start out with more than one Reynolds-Viscek agent in its neighborhood, even with the *k-means* placement behavior. As a result, even the best clustering approach is almost the same as starting out randomly or in a grid.

6.1.3 INFLUENCING AGENTS IN THE HERD SETTING

Next, we evaluate results for our experiments in the *herd* setting. In many cases, measuring the number of agents facing the same direction is not interesting here, since it is impossible to keep Reynolds-Viscek agents in one place if they are facing the same direction. Instead, we exclusively measure the number of Reynolds-Viscek agents that are path-connected to influencing agents and facing the same direction as the influencing agent. This is a measure of “control” of the Reynolds-Viscek agents. The average number of agents in such local flocks after 15000 time steps is given in Figure 6.4 for both the net and stationary behaviors. We find that the net behavior vastly outperforms any of the stationary behaviors. However, there may be environments in reality for which the net behavior is not applicable (suppose it is strictly necessary to keep a flock in one place, for instance). Thus, we

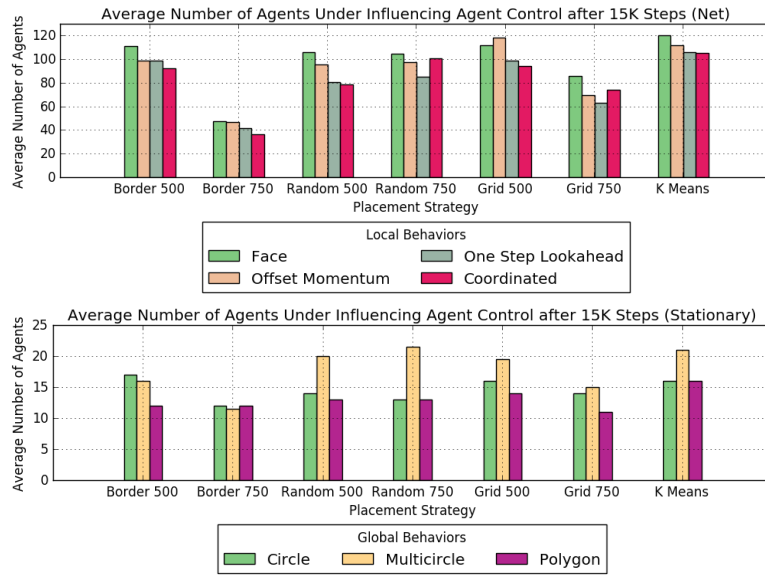


Figure 6.4: Average number of agents under influencing agent control after 15000 steps with 300 Reynolds-Viscek agents and 50 influencing agents in the *herd* setting under for various placement strategies and influencing agent behaviors. The net behavior moves the influencing agents and their Reynolds-Viscek agents off-screen, while the stationary behaviors keep the influencing agents near the goal area using some sort of circling technique. For the stationary behaviors, we found the only effective local behavior was *face*, so it is the only local behavior displayed. Larger is better.

analyze the net behaviors separately from the stationary behaviors.

NET

Again, we find that the *face* local behavior tends to outperform the *offset momentum*, *one step lookahead*, and *coordinated* local behaviors. Again, we attribute this to the tendency of the *offset momentum*, *one step lookahead*, and *coordinated* behaviors to lose influence over time. We note that the effect is not as pronounced here as in our *large* experiments, since each influencing agent has to control fewer agents.

In contrast to the *large* experiments, we do find that the placement strategy has a major effect on the efficacy of the net behavior. Again, this has to do with density of influencing agents. For example, notice that *Border 750* (place the influencing agents in a circle about the origin with radius 750) vastly underperforms the other placement strategies. The larger radius results in a lower density of influencing agents, so a greater number of Reynolds-Viscek agents slip through the “holes” in the net. Furthermore, by the time the Reynolds-Viscek agents reach the border, they have already formed local flocks, and it is more difficult for the influencing agents to point them in the right direction. This effect is less pronounced for *Random 750* and *Grid 750*, since these strategies place influencing agents within the circle, and not simply along its circumference. As a result, the Reynolds-Viscek agents still encounter influencing agents before reaching the circumference of the circle.

Finally, we note that *k-means* outperforms all other placement strategies by a few agents. Again, the main driving factor behind this is agent density. When an influencing agent starts out in a clus-

tered area, it has at least one other Reynolds-Viscek agent in its neighborhood. As a result, its effective area of influence is slightly larger than with the other placement strategies. This helps it pick up more Reynolds-Viscek agents in the net.

STATIONARY

For the stationary behaviors, we found that any local behavior except for *face* was almost completely ineffective; the average number of agents under influencing agent control after 15000 steps across 100 trials was almost 0. Again, this is a result of the inability of the *offset momentum*, *one step lookahead*, and *coordinated* local behaviors to maintain influence over time. Each of the stationary behaviors requires the influencing agents to keep the Reynolds-Viscek agents rotating about the origin in some way. Without consistent influence, this is impossible.

Beyond that, we find that the *multicircle* behavior slightly underperforms the *circle* behavior when paired with the *Border* placement strategies, but slightly overperforms when paired with the *k-means*, *Random*, *Circle*, and *Grid* placement strategies, and performs the same as *circle* in the *Grid* strategies. What drives these trends? Once *multicircle* reaches the final stage, it is tracing a larger circle than the *circle* behavior traces on its own. As a result, it is easier to maintain influence and turn the Reynolds-Viscek agents over time in the final stage. Before that, however, the influencing agents are in a following stage. When the influencing agents start out inside the circle, they have more time to infiltrate small flocks of Reynolds-Viscek agents and induce a circling behavior in the final stage.

Finally, we note that *Border 750* is the worst placement strategy, for reasons similar to the reasons for the net behaviors, and *polygon* tends to underperform or match the performance of *circle*. This

tells us that adopting occasional sharper turns can sometimes be harmful, but not always.

6.2 RADHIKA RESULTS

6.2.1 EVOLUTIONARY EXPERIMENTS

We ran a total of 5 evolutionary runs. The first four had population size 25 and ran for 50 generations, while the last one had population size 100 and ran for 300 generations. For the first four runs, we selected the top 10 genomes to seed the next generation. For the last run, we selected the top 20 genomes. As an optimization, we memoized genomes from generation to generation and re-used results where possible. We allowed for duplicate members in the population. The average angle difference across the population and the angle difference of the best genome in each generation are shown in Figure 6.5.

In each run, the population converged to one or two best genomes that remained in the seed population for every generation. These best genomes consistently outperformed the hand-constructed local behaviors taken from the literature. However, the average angle difference across the population stayed relatively high throughout the entire simulation, since the majority of the population were the results of random mutation or crossover from the seed population. In many cases, the new children perform very poorly, driving the average angle difference up. In the last run, with a population of size 100, there is a sharp drop in the average angle difference around generation 160. At this point in the evolutionary run, a single genome out-competed all the others. As a result, all subsequent populations were seeded by multiple copies of a single genome, and mutations/crossover

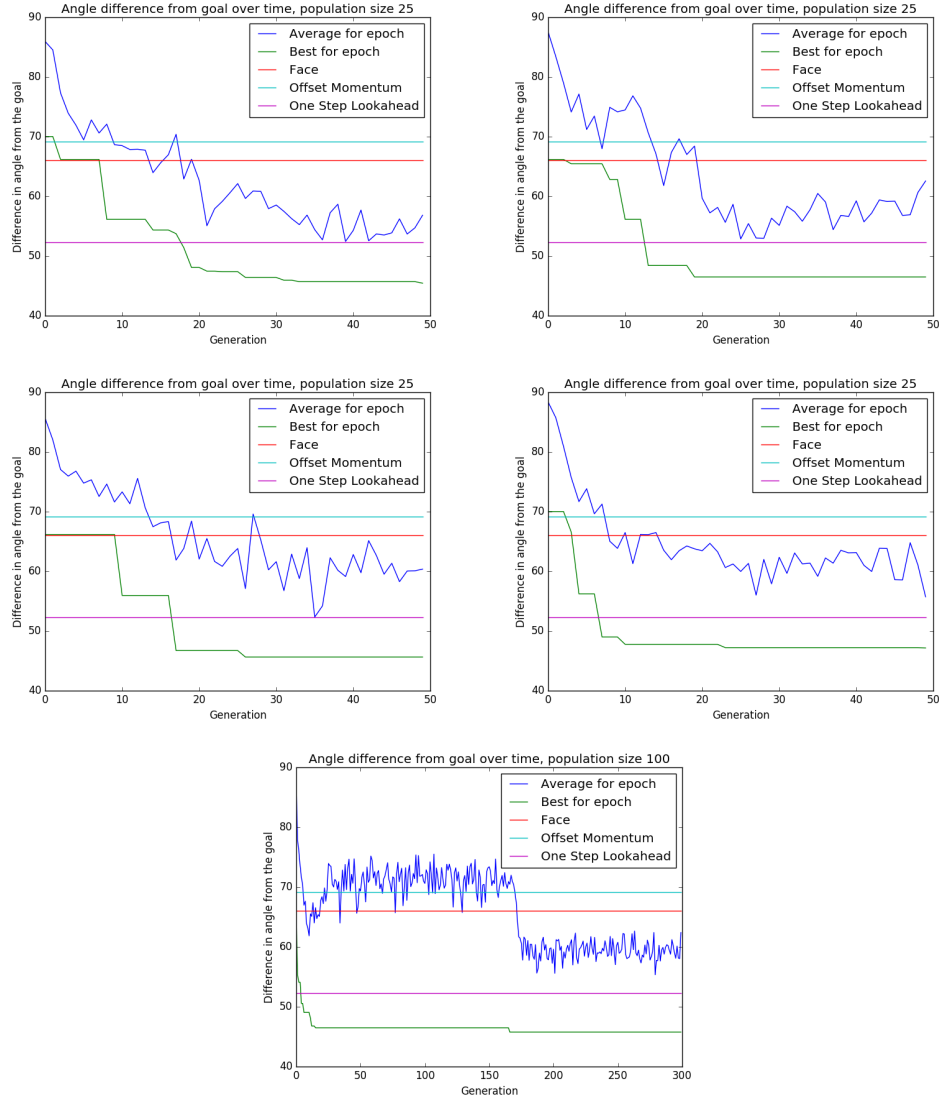


Figure 6.5: Average population fitness and fitness of the best candidate in the population over generations for a five different runs of the genetic algorithm. The first four runs had population size 25 and ran for 50 generations, while the last run has population size 100 and ran for 300 generations. Fitnesses of *face*, *offset momentum*, and *one step lookahead* provided for comparison.

performed on this seed population were relatively stable.

From these five evolutionary runs, we selected 7 for further analysis. These are shown in Table

6.1 These genomes bear a few similarities to each other; they all initialize the accumulator to the goal

Name	Genome
G1	acc=goal; (mul acc (gez (cos heading) (exp (sin heading) distance) (sin goal))))
G2	acc=goal; (mul influence (mul influence goal))
G3	acc=goal; (sub acc (mul -0.2678771899171444 goal))
G4	acc=goal; (mul (mul acc (cos heading)) distance)
G5	acc=goal; (mul distance (mul (sub (sub goal 0.2801770623593902) heading) (mul (sub acc heading) goal))))
G6	acc=goal; (mul distance (mul (sin influence) (mul (sub (sub goal 0.2801770623593902) heading) (mul (sub (sub goal 0.2801770623593902) heading) goal))))))
G7	acc=goal; (mul goal (gez (cos acc) 0.19745673470999736 goal))

Table 6.1: Genomes from evolution

direction, for example. Beyond that, they share very little in common. Some genomes (G1, G3, G5, G7) use the accumulator, while the others do not; some are short and easy to parse (G2 is equivalent to $\frac{goal}{N^2}$, where N is the number of neighbors), while others are much more complicated.

Although they may be very different in expression, they are very similar to each other in execution. When all the agents are already facing east, these behaviors all have the influencing agent face east as well. In addition, they pick up some gains from the north and south starting conditions by initially picking up more neighbors than the baseline conditions. They pick up some major gains in the west case, where they intersect a few of the neighbors to their east side and lead them towards the target direction over the course of the next 100 steps. A few screenshots of this process are shown in Figure 6.6. The other genetic processes behave very similarly to the behavior shown in the screenshots, with slight variations (i.e., turning north instead of south, etc).

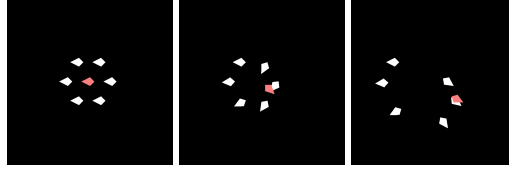


Figure 6.6: Screenshots of the G1 local behavior when trying to turn 6 Reynolds-Viscek agents 180 degrees to the east. Instead of trying to turn all 6 neighbors at once, as the *one step lookahead* behavior does, the genetic behavior “gives up” on some neighbors and just tries to turn the neighbors that are behind it.

This behavior is very interesting scientifically for the differences between it and *one step lookahead*. In particular, the genetic behaviors immediately turn towards the Reynolds-Viscek agents behind them, and ignore the agents in front of them. There are two major insights we can glean from this behavior. First, when the influencing agents focus on the agents behind them, they can successfully maintain influence over time instead of flying away from the flock as they try to turn their neighbors towards the goal direction. In other words, the genetic behaviors implicitly value influence over rapid convergence. We hypothesize that this arises because evaluation happens after 100 steps and not after 1 step, as with *one step lookahead*, but more work is needed to answer this definitively.

Second, the influencing agents ignore the Reynolds-Viscek agents in front of them. There are a few reasons why this is beneficial. Since the influencing agents have limited speed, they can never “catch up” to the agents directly in front of them. The *one step lookahead* algorithm does not take this into account; as long as a neighbor is in range, its heading is factored into the calculation, no matter whether the influencing agent can ever reach the neighbor. Furthermore, it is much easier to lose influence over forward neighbors, since any change in direction necessarily means that the influencing agent falls behind. Thus, the Reynolds-Viscek agents in front are somewhat of a lost

cause, and it is beneficial to ignore them.

6.2.2 INFLUENCING AGENTS IN THE LARGE SETTING

Next, we verify that the genetic algorithms are still effective when used in larger settings and in conjunction with global behaviors and placement strategies. For example, *one step lookahead* outperforms *face* in the small-scale evaluations we use during evolution, but underperforms *face* in simulations in the *large* setting. To remind the reader, the *large* setting places Reynolds-Viscek agents randomly on a toroidal 1000x1000 grid with random initial orientations. We evaluate our genetic behaviors paired with three placement strategies (*random*, *grid*, and *k-means*), and three global behaviors (*direct*, *random*, and *multistep*). We place 300 Reynolds-Viscek agents on the simulation space and use 50 influencing agents. We measure the number of steps necessary to reach 50% convergence (150 Reynolds-Viscek agents all facing the same direction), measuring metrics every 100 time steps and averaging over 100 trials. The results are shown in Figure 6.7.

We find that the efficacy of the genetic behaviors varies depending on the global behavior. In particular, the genetic behaviors all perform on par with, or slightly better than, the *face* local behavior when paired with the *direct* global behavior. They all strongly outperform the *one step lookahead* local behavior and slightly outperform the *offset momentum* local behavior.

When paired with the *random* global behavior, however, the story changes drastically. Genetic behaviors G1, G4, and G7 still perform on par with the *face* local behavior, but G2, G3, and G6 start performing as poorly as *one step lookahead*. G5 takes a major hit; instead of converging within 4000 timesteps, it takes up to 30000 timesteps to converge. From watching the simulations, a very pe-

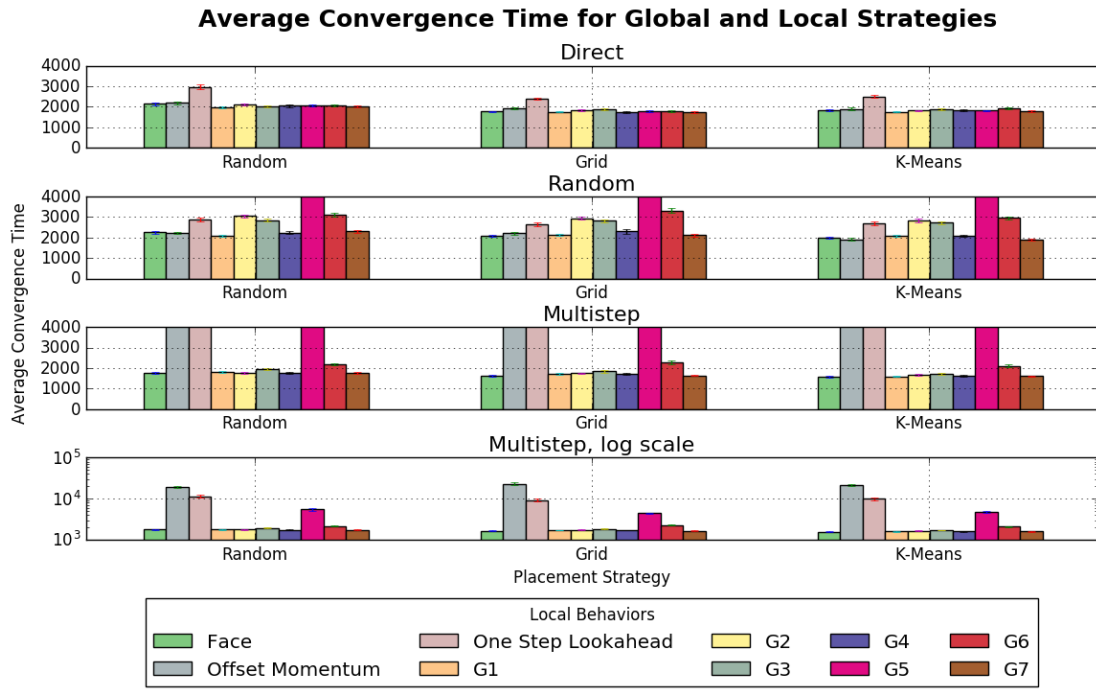


Figure 6.7: Average times to 50% convergence for 300 Reynolds-Viscek agents with 50 influencing agents in the *large* setting under different placement strategies, paired with various global and local behaviors. The *Random* global behavior paired with the *G5* local behavior performs very poorly; average convergence times are upwards of 30000. Smaller is better.

culiar behavior emerges: when the influencing agent is moving in a random direction and meets a flock moving in a similar direction, the agent continues moving in the direction of the flock instead of turning the flock towards the goal direction. It is not clear to us why this behavior emerges, especially since G5's genome is one of the harder genomes to parse.

When paired with the *multistep* global behavior, G1-3 once again perform on par with the *face* local behavior. The G5 behavior again performs much worse, and the G6 behavior performs slightly worse than the *face* local behavior. G4 and G7 perform slightly better than G1-3, and slightly outperform *face* (though not by a significant amount). Notably, none of the genetic behaviors, not even G5, perform as badly as *offset momentum* and *one step lookahead* do when paired with the *multistep* global behavior. This is promising; it suggests that there are behaviors that can be more effective than *face* on a small scale but that can remain effective even when moving to low-density settings.

7

Conclusion

7.1 BARBARA CONCLUSION

We have studied the problem of controlling flocks using influencing agents under two new, more adversarial environments with lower agent density, and have introduced some novel behaviors and placement strategies for these settings. Besides these new algorithms, we have found that, in low-density environments it is more important for influencing agents to *maintain influence* than it is

for them to rapidly turn their neighbors towards the correct destination. As a result, earlier results from smaller simulation environments often do not hold in the environments we introduce. We have found that a multistage approach that first embeds influencing agents in small flocks before attempting to steer these flocks to the goal direction can be effective in addressing some of these shortcomings.

Future work could explore the design space of placement strategies and agent behaviors by applying machine learning techniques to this problem. Future work could also explore how to aggregate small flocks into one larger flock. Many of our behaviors result in multiple small flocks clustered around influencing agents that have converged in the sense that they are all facing the same direction, but remain disconnected from each other. An interesting challenge would be to develop algorithms to merge small flocks that start out with the same orientation, while maintaining flock composition. For this challenge, a successful algorithm for an influencing agent must change the direction of the flock without losing individual Reynolds-Viscek agents on the edge of the flock.

7.2 RADHIKA CONCLUSION

In this paper, we have presented an evolutionary algorithm that evolves ad hoc algorithms for influencing agents to control flocks of birds. We evolved a genome based on a hand-constructed domain-specific language and found that many of the evolutionary algorithms incorporated non-trivial insights about the best way to be successful in a wide range of settings. However, we also found that the evolved behaviors could be difficult to parse and somewhat unpredictable, especially when used as parts of more complicated behaviors.

In the future, we plan on conducting a more thorough analysis of these genetic behaviors in a wider range of evaluation settings. We also wish to explore the design space of genetic algorithms more deeply by evolving behaviors over different genomes, such as neural networks. Another promising direction of research is to co-evolve different aspects of influencing agent behavior to help agents co-ordinate in previously unexpected ways. Finally, we could also explore the design space in a different way by taking techniques from reinforcement learning.



Some extra stuff

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References

- [1] Briggs, F. & O'Neill, M. (2008). Functional genetic programming and exhaustive program search with combinator expressions. *Int. J. Know.-Based Intell. Eng. Syst.*, 12(1), 47–68.
- [2] Chen, Y., Wang, H., Helbling, E. F., Jafferis, N. T., Zufferey, R., Ong, A., Ma, K., Gravish, N., Chirarattananon, P., Kovac, M., & Wood, R. J. (2017). A biologically inspired, flapping-wing, hybrid aerial-aquatic microrobot. *Science Robotics*, 2(11).
- [3] Couzin, I. D., Krause, J., Franks, N. R., & Levin, S. A. (2005). Effective leadership and decision-making in animal groups on the move. *Nature*, 433.
- [4] de Castro, L. N. (2007). *Evolutionary Computing*, chapter 3, (pp. 105–108). Chapman & Hall/CRC.
- [5] Dorigo, M., Trianni, V., Şahin, E., Groß, R., Labella, T. H., Baldassarre, G., Nolfi, S., Deneubourg, J.-L., Mondada, F., Floreano, D., & Gambardella, L. M. (2004). Evolving self-organizing behaviors for a swarm-bot. *Auton. Robots*, 17(2-3), 223–245.
- [6] Fu, D. Y., Wang, E. S., Krafft, P., & Grosz, B. (July 2018). Design of influencing agents to aid flock formation in low-density settings. In *Proceedings of the 2018 International Conference on Autonomous Agents and Multiagent Systems (AAMAS-18)*.
- [7] Genter, K. (2017). *Fly with Me: Algorithms and Methods for Influencing a Flock*. PhD thesis, The University of Texas at Austin.
- [8] Genter, K., Agmon, N., & Stone, P. (2013a). Ad hoc teamwork for leading a flock. In *Proceedings of the 12th International Conference on Autonomous Agents and Multiagent Systems (AAMAS 2013)*.
- [9] Genter, K., Agmon, N., & Stone, P. (2013b). Improving efficiency of leading a flock in ad hoc teamwork settings. In *AAMAS Autonomous Robots and Multirobot Systems (ARMS) Workshop*.

- [10] Genter, K. & Stone, P. (2014). Influencing a flock via ad hoc teamwork. In *Proceedings of the Ninth International Conference on Swarm Intelligence (ANTS 2014)*.
- [11] Genter, K. & Stone, P. (2016a). Ad hoc teamwork behaviors for influencing a flock. *Acta Polytechnica*, 56(1).
- [12] Genter, K. & Stone, P. (2016b). Adding influencing agents to a flock. In *Proceedings of the 15th International Conference on Autonomous Agents and Multiagent Systems (AAMAS-16)*.
- [13] Genter, K., Zhang, S., & Stone, P. (2015). Determining placements of influencing agents in a flock. In *Proceedings of the 2015 International Conference on Autonomous Agents and Multiagent Systems (AAMAS-15)*.
- [14] Halloy, J., Sempo, G., Caprari, G., Rivault, C., Asadpour, M., Tâche, F., Saïd, I., Durier, V., Canonge, S., Amé, J. M., Detrain, C., Correll, N., Martinoli, A., Mondada, F., Siegwart, R., & Deneubourg, J.-L. (2007). Social integration of robots into groups of cockroaches to control self-organized choices. *Science*, 318(5853), 1155–1158.
- [15] Han, J., Li, M., & Guo, L. (2010). Soft control on collective behavior of a group of autonomous agents by a skill agent. 19.
- [16] Jadbabaie, A., Lin, J., & Morse, A. S. (2003). Coordination of groups of mobile autonomous agents using nearest neighbor rules. *IEEE Transactions on Automatic Control*, 48(6), 988–1001.
- [17] Liang, H., Yang, Y., & Wang, X. (2013). Opinion dynamics in networks with heterogeneous confidence and influence. *Physica A*, 392.
- [18] Luke, S. (1998). Genetic programming produced competitive soccer softbot teams for RoboCup97. In J. R. Koza, W. Banzhaf, K. Chellapilla, K. Deb, M. Dorigo, D. B. Fogel, M. H. Garzon, D. E. Goldberg, H. Iba, & R. Riolo (Eds.), *Genetic Programming 1998: Proceedings of the Third Annual Conference* (pp. 214–222). University of Wisconsin, Madison, Wisconsin, USA: Morgan Kaufmann.
- [19] Luke, S., Cioffi-Revilla, C., Panait, L., Sullivan, K., & Balan, G. (2005). Mason: A multi-agent simulation environment. In *Simulation: Transactions of the society for Modeling and Simulation International*.

- [20] Olfati-Saber, R. (2006). Flocking for multi-agent dynamic systems: algorithms and theory. *IEEE Transactions on Automatic Control*, 51(3), 401–420.
- [21] Reynolds, C. W. (1987). Flocks, herds and schools: A distributed behavioral model. In *Proceedings of the 14th Annual Conference on Computer Graphics and Interactive Techniques*, SIGGRAPH '87.
- [22] Schruben, L. W. & Singham, D. I. (2010). Simulating multivariate time series using flocking. In *Proceedings of the 2010 Winter Simulation Conference*.
- [23] Segerman, H. (2010). The sunflower spiral and the fibonacci metric.
- [24] Singham, D., Therkildsen, M., & Schruben, L. (2011). Applications of flocking algorithms to input modeling for agent movement. In *Proceedings of the 2011 Winter Simulation Conference*.
- [25] Su, H., Wang, X., & Lin, Z. (2009). Flocking of multi-agents with a virtual leader. *IEEE Transactions on Automatic Control*, 54(2), 293–307.
- [26] Sumpter, D. J. (2010). *Collective animal behavior*. Princeton University Press.
- [27] Sumpter, D. J., Krause, J., James, R., Couzin, I. D., & Ward, A. J. (2008). Consensus decision making by fish. *Current Biology*, 18.
- [28] Vaughan, R., Sumpter, N., Frost, A., & Cameron, S. (1998). Robot sheepdog project achieves automatic flock control. In *From Animals to Animats 5: Proceedings of the Fifth International Conference on the Simulation of Adaptive Behaviour* (pp. 489–493).: MIT Press.
- [29] Vicsek, T., Czirók, A., Ben-Jacob, E., Cohen, I., & Shochet, O. (1995). Novel type of phase transition in a system of self-driven particles. *Phys. Rev. Lett.*, 75, 1226–1229.
- [30] Yang, W., Cao, L., Wang, X., & Li, X. (2006). Consensus in a heterogeneous influence network. *Physical Review E*, 74.



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