Project Summary

Black Soldier Fly larvae (BSFL) farms are being developed around the world as an efficient and sustainable way to recycle organic waste. These farms feed BSFL on organic waste and then use the larvae as protein-rich animal feed. In vats of eating BSFL, video and particle tracer analysis has revealed patterns that resemble vortices and tori, which might function to increase eating rate. In order to understand how these structures arise, an agent-based model (ABM) was created of a single Black Soldier Fly larva foraging in a circular container for food. The larva randomly moves around, prefers to follow the container boundary, and eats when it finds the food source. A genetic algorithm optimized the ABM parameters to match simulations to physical experiments. Comparison with these physical experiments showed that the ABM accurately replicated key eating and wall following behaviors, and it robustly accounted for a criteria not explicitly optimized. More experimental data is necessary to investigate the variance in eating behavior of BSFL, especially over different growth stages. Future work includes inferring larvae characteristics and accounting for multiple larvae. An ABM simulating aggregations of BSFL could eventually guide the placement of food sources to maximize eating rate in BSFL farms

Objective Statement

The goal of this project is to model the eating behavior of a single Black Soldier Fly larva in order to provide the first step in understanding the mechanics of their collective motion.

Problem

What are the individual and collective eating patterns of Black Soldier Fly larva?

Hypothesis

If the feeding behavior of a single Black Soldier Fly larva is modeled, then a model of Black Soldier Fly larvae aggregations can be extrapolated.

Background

Black Soldier Fly larvae (BSFL)

- Voracious and rapid eaters
- Small in size
- Capable of recycling urban solid waste
- Several business enterprises focused on BSFL recycling (1)

Figure 1: Black Soldier Fly larva are about 20 mm in length and 5 mm in width.

Figure 2: Grubbly Farms sells BSFL as chicken feed.

Physical Experiments

- Particle-tracer and video analysis at Georgia Tech (2)
- Vortices (position 1) and tori (position 2) around food source
- BSFL vortices resemble schools of fish and flocking birds (3-4)
- Individual larva behavior from video data
- 10 larva move and eat in petri dish for 1 hour
- Larva behavior measured from video

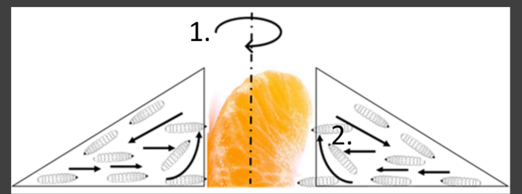


Figure 3: 1: Active mixing of the larvae creates a vortex. 2: Larvae are displaced upward then fall away, creating a torus.

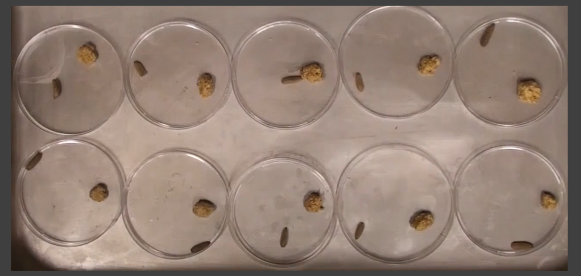


Figure 4: The setup of the experiment is 10 petri dishes containing a single BSFL and a food source.

Agent-Based Modeling

- Reveals emergent behavior of interacting **agents**
- Agents reside in an **environment** and follow **rules**
- **Parameters** determine the rules and are inputs to the model
- In Flocking (5) from Netlogo (6) birds self organize without a lead bird

Rules

- Alignment: turn in same direction as surrounding birds
- Separation: turn away from too close birds
- Cohesion: long range attraction between birds
- Move: simple forward movement

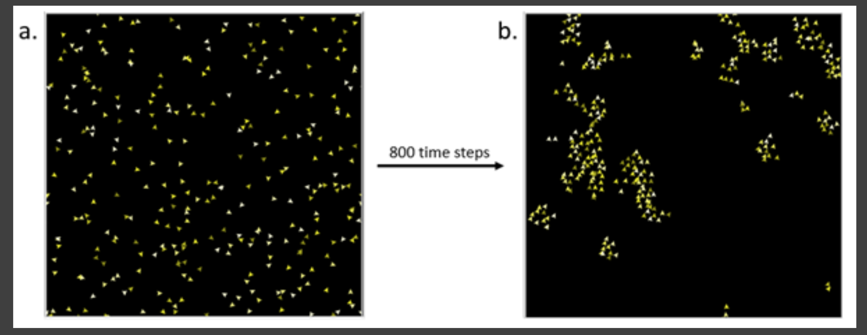


Figure 5: (a) The initial random orientation and distribution of the birds in Flocking. (b) Birds are in clumps and aligned in the same direction.

Genetic Algorithm

- Optimization technique inspired by natural selection
- Optimizes parameters in a model to based on a fitness function
- Three main operators in genetic algorithm
  - Selection
  - Crossover
  - Mutation

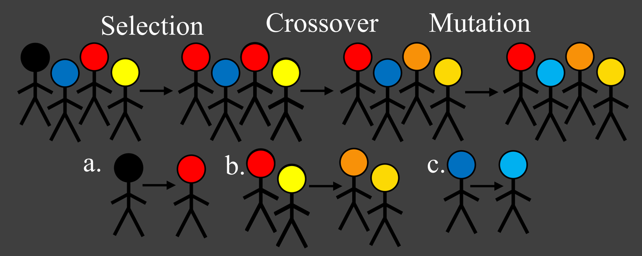


Figure 6: (a) Selection chooses individuals red, blue, red, then yellow; black is left out. (b) Crossover blends red and yellow into dark orange and light orange. (c) Mutation changes dark blue to light blue.

Foraging Behavior of a Black Soldier Fly Larva: An Agent-Based Modeling Simulation Study

Methods

1. Agent-Based Model Composition

- **Agent** is a single larva
- **Environment** mimics physical experiments
- **Rules**
  - Wiggle: random adjustment of direction
  - Align: follow boundaries (i.e. the petri dish)
  - Move: simple forward movement
  - Eat: for a duration from physical experiments
- **Parameters**
  - wiggle-amount: magnitude of wiggle turning (degrees)
  - wiggle-often: how often wiggle occurs (percentage)
  - max-align-turn: magnitude of align turning (degrees)
  - vision: distance ahead the larva can detect (distance)
  - food-xcor: x-coordinate of the location of food (point)

Figure 8: A side by side comparison between an experiment setup and the model setup. Both have a larva with a source of food near the edge of the petri dish.

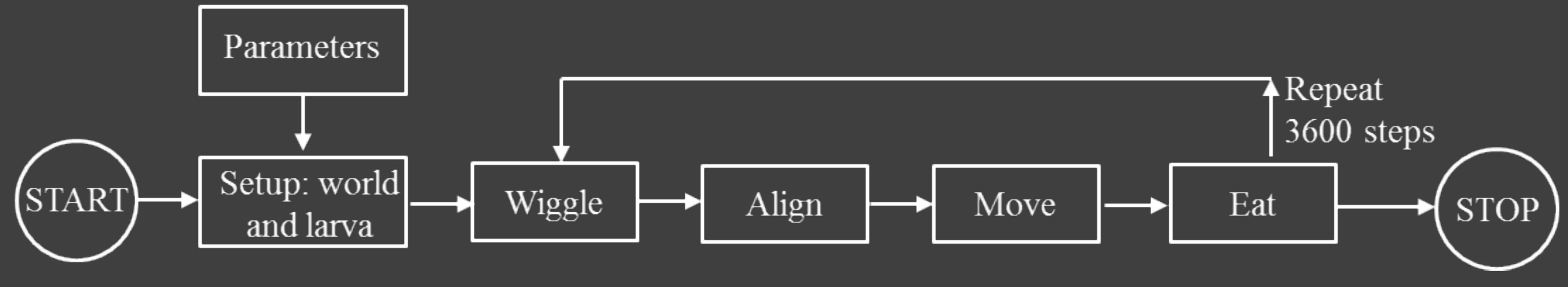


Figure 9: This flowchart shows the progression of the BSFL ABM code. Boxes denote steps, and diamonds denote branches in the flow.

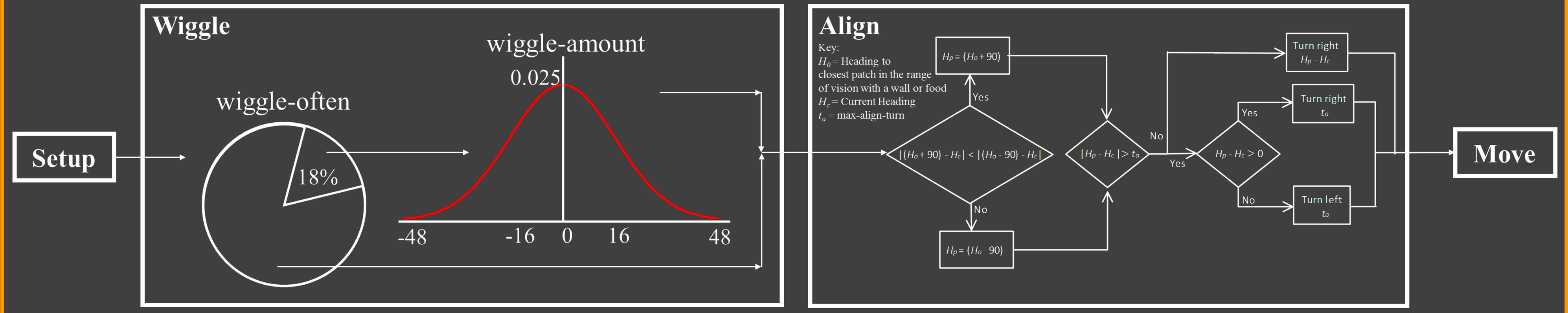
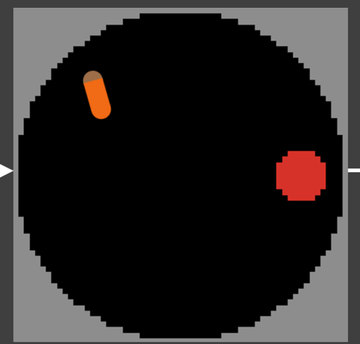


Figure 10: The procedure of the wiggle and align methods is shown. Here, wiggle-often is 18% and wiggle-amount is 16 degrees. The align part of the diagram shows the mathematical reasoning of the method.

2. Genetic Algorithm Optimization

Parameters
wiggle-amount
wiggle-often
max-align-turn
vision



	Physical experiment	Simulation
Time eating	26.0%	*f*
Time on wall	62.9%	*w*
Time in middle	11.1%	*m*

$$\frac{\left(\frac{f-0.26}{0.26}\right)^2+\left(\frac{w-0.629}{0.629}\right)^2+\left(\frac{m-0.111}{0.111}\right)^2}{3}$$

Figure 11: The genetic algorithm's purpose is to find the optimal parameter set by minimizing the function.

Optimization Steps

1. Choose parameter set
2. Input parameter set into ABM
3. Record data of Time eating, Time on wall, and Time in middle
4. Input recorded data into the fitness function
5. Adjust parameter set to decrease fitness
6. Repeat steps 1-5 until fitness is minimized

Results

Optimal Parameter Set

- The optimized parameter set minimizes error
- Multiple viable parameter sets exist out the thousands tested
  - The precise value of the parameter set has less meaning than the rules which use them

Table 1: An optimized parameter set for the ABM.

Parameter	wiggle-amount (degrees)	wiggle-often (percentage)	max-align-turn (degrees)	vision (distance)
value	16	18	83	3

Model Accuracy

- Time eating and Time on the wall are key larva behaviors
- Very accurate model
- Eating instances per hour not explicitly optimized in the Genetic Algorithm
- Accurately extrapolates larva behavior

Table 2: Comparison of physical experiments and simulation.

	Physical experiment	Simulation
Time eating	26.0%	24.8%
Time on wall	62.9%	62.0%
Eating instances per hour	6.5	4.25

Larva Behavior

- Larva behavior can be inferred by the model's rules and parameters since it is accurate and robust
- Varying a parameter while holding the others constant shows the effect of the individual parameter on larvae behavior
- Small variations in selected parameters effect Time eating and Time on the wall

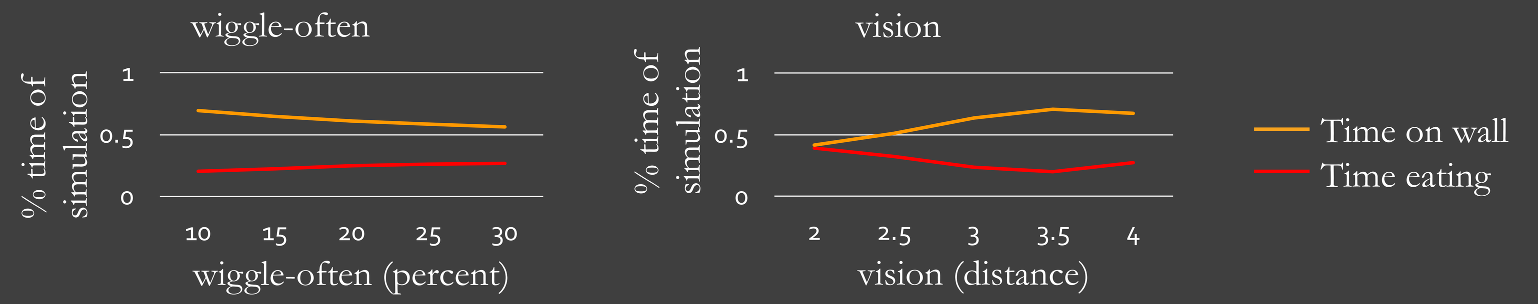


Figure 12: The graphs above compare the parameters wiggle-often and vision to the percent time on wall and eating.

- The slope of the Time eating line indicate whether the parameter correlates positively or negatively with eating
  - The positive slope of Time eating for wiggle-often indicates the wiggle rule has a positive effect on time spent eating.

- Random wandering encourages a larva to explore to find the food, increasing eating
- Boundary following keeps a larva on the edge of the petri dish away from the food in the center of the dish, decreasing eating

Table 3. Correlation of parameters with larva behavior.

Parameters	Larva Behaviors	Eating
wiggle-amount	Random wandering	More
wiggle-often		
max-align-turn	Boundary following	Less
vision		

Conclusions and Future Work

Conclusions

- An agent-based model of individual Black Soldier Fly larva was created
- With parameters optimized by a genetic algorithm, the model was accurate and robust
- Larva preferentially moved along boundaries even though random movement finds food more frequently

Future work

- Modeling aggregations of larvae by adding larvae interactions and 3 dimensional movement
- Easy extrapolation since model was coded as an Agent Based-Model
- Building the single larva model as an agent-based model allows easy transition to a model of aggregations

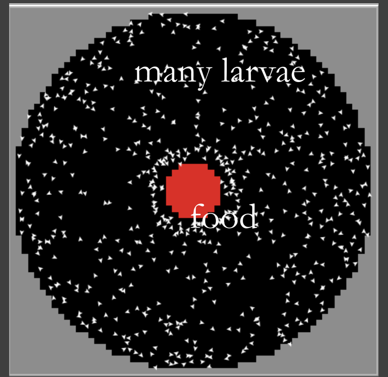


Figure 13: Initial larvae aggregation model

References

1. *Black Soldier Fly Biowaste Processing - A Step-by-Step Guide*. **Dortmans B. M. A., Diener S., Verstappen B. m., Zurbrügg C**. 2017, Eawag: Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland.
2. Black Soldier Fly larvae consume food by actively mixing. Shishkov, O., Hu, M., Johnson C., Zhang, B., Hu., D. L. Tokyo : s.n., 2018. 7th International Symposium on Aero-aqua Bio-Mechanisms.
3. *The principles of collective animal behaviour*. **DJ, Sumpter.** 2006, Philosophical Transactions of the Royal Society of London B: Biological Sciences., pp. 5-22.
4. *Three-dimensional trajectories and network analyses of group behaviour within chimney swift flocks during approaches to the roost.* **Evangelista DJ, Ray DD, Raja SK, Henrick TL.** 2017, Proc R Soc B.
5. Wilensky, U. (1998). NetLogo Flocking model. http://ccl.northwestern.edu/netlogo/models/Flocking. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.
6. Wilensky, U. (1999). NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.