Order in Chaos: an Algorithmic Approach to Flocking Behavior

An Honors Thesis Proposal

Important Note

The research for this project has already been completed and the results are currently being drafted to be submitted to a publisher. This project is an extension of the work done for my physics senior thesis (which is required for me to graduate) and the work has already been approved by the Physics Department.

A. Statement of Intent

I am seeking to establish a greater understanding of the characteristics of emergence in chaotic systems by studying simplified models of self-propelled particles that reflect the behavior of starling murmurations.

B. Background and Significance

With the rise of more sophisticated computers also came a rising interest in chaos theory. A chaotic system is one that is determined from the beginning but which will produce extremely different results from small parameter changes. The classic examples of these are the butterfly effect described in Jurassic Park, and a driven double pendulum. Application of chaos theory to complex systems was soon proposed after the first papers on the subject appeared.[1] Even so, actually defining what a chaotic system is or what a complex system is can be difficult at times as well as defining the nature of emergence.[2] Different types of chaotic and complex systems have been described[3] and they each can be applied to various situations. I will be applying chaos theory and complexity theory to previous work done on modelling bird flocking behavior.

Shortly before the 1990s Reynolds developed a computational model to simulate the motion of a flock of birds.[4] He coined the term "boid" as a shortened term for bird-oid, which is essentially a self-propelled particle that imitates the behavior of a bird. His model was based upon an averaging of nearest-neighbor velocities. Later work was developed by Viscek who also built upon nearest-neighbor averaging.[5] While these models have their qualities, the results that demonstrate emergence have seemed to lack in true flocking behavior. As such, my advisor Dr. Manuel Berrondo along with his former student Wesley Krueger[6], proposed a new model type for replicating dynamic flocking behavior.[7] The new model abandons the notion of a nearest-neighbor interaction in favour of a topological interaction (referred to as flockmates). This new model gives rise to more dynamic behavior with fewer parameters, and also led to more emergent behavior with a simpler form of frustration or perturbation.

I will be working to improve upon Dr. Berrondo's model. I am seeking to add to the discussion of being better able to define the characteristics of emergence, particularly through the filter of flocking behavior. By adding to, and modifying Berrondo's model I will be able to more extensively explore the relationship between simple individual interactions and group behavior.

C. Methodology

I will be following the same methodology described by my faculty advisor in his original paper, only with differences in which model is used. Thus I will be taking the code used to run the simulations and analyzing it using an alignment order parameter and a rotational order parameter both for the entire flock and for specific subgroups of flockmates. Then, using these two unique order parameters I will also visually determine whether or not that particular simulation is emergent. I will do this for a determined set of variables that are similar to the parameter space surveyed in the original work. That way comparisons can be made to the previous work, while simultaneously building upon the emergence characterization discussion.

The two order parameters are significant in how they reveal unique, but correlated information regarding the uniformity of the flock as well as the flockmates. The alignment order parameter, <v(t)>, is calculated by taking the sum of the velocities of each boid, modulus, and then normalizing it. Thus a value of one would mean every boid is flying in exactly the same direction while a value of zero would be complete randomness, or extreme rotational motion. Additionally, the rotational order parameter, L(t), is calculated by finding the curvature of each boid over a given number of time steps and then averaging the curvature of all of the boids in the flock.

$$\langle v(t) \rangle = \frac{1}{N v_0} \left| \sum_{i=1}^{N} \vec{\mathbf{v}}_i(t) \right| \qquad L(t) = \frac{1}{N} \sum_{i=1}^{N} \frac{1}{z} \sum_{t=1}^{z} \frac{v_i(t) \wedge v_i(t+1)}{v_0^2}$$

D. Preliminary Outline or Prospectus of the Finished Thesis

I will be following the standard convention of my department for writing my thesis. I expect my project to contain the following categories:

1. Introduction and Background
   - Context and literature review of the subject.

- This review will include a brief summary of the Reynolds and Viscek models as well as the observational works of Cavagna and his group.

2. Model
   - Here I will elaborate on the innovations of the model and describe its uniqueness and characteristics.
3. Results
   - Here I will include a series of plots and figures that help to clarify, classify, and characterize emergence.
4. Discussion
   - Here I will compare the new results that I have discovered with the previous results of the model and share any insights into the model's uniqueness and capabilities.
5. Conclusion
   - A simple wrap-up of the purpose, results, and discussion.
6. Appendix
   - Translating the model from MATLAB to *Mathematica.*
7. Bibliography
   - In order of citation in the paper.

E. Preliminary Research

I have already worked with my faculty advisor and completed almost all of the research for the project, including the analysis of the results. The work that I have done has built upon the works mentioned in the Background and Significance section. I intend to use around twenty peerreviewed published works that build on the discussion of emergence, chaos, and flocking behavior, as part of my literature review. These articles will address the initial discussion of emergence, the development of self-propelled flocking models, and the method developed by Dr. Berrondo, Wes Krueger, and Dr. Sandoval[8] including mentions to Dr. Cavagna's work in tracking flocking behavior observationally. Some of these articles are listed in the bibliography at the end of this proposal.

My advisor and I have already completed all of the quantitative research necessary to add to the discussion of emergence characterization.

F. Qualifications of the Investigators

I have completed almost all of the required courses for a physics major, on top of completing a math minor, and almost completed a computer science minor. The skills and techniques that I have acquired for this project far exceed the skills required. I have also been doing computational physics research with Dr. Berrondo for about 14 months now, so I have lots of hands on experience. I've also presented some of this research at the annual American Physics Society - Four Corners (APS4C) meeting in 2015 and at the CPMS Student Research Conference in 2016.

G. Qualifications of the Faculty Advisor

Dr. Manuel Berrondo is a professor in the Department of Physics and Astronomy at Brigham Young University and he has considerable experience in theoretical physics. The model that I will be working with is an extension and continuation of his model. Additionally, his model has been successful and he has already published some of results.

H. Schedule

June-July 2015

- Literature review and background development

August-October 2015

- Translate model from MATLAB to *Mathematica*

October 2015

- Present preliminary research at APS4C meeting

November 2015 - March 2016

- Develop modified and improved model
- Obtain new results and improved characterization

March 2016

- Present new results at BYU's CPMS Student Research Conference.

April-June 2016

- Analyze new results
- Develop figures
- Write preliminary drafts for paper

July-December 2016

- Write and polish thesis

(Vika): I would make sure he knows specific deadline for Honors.

I. Expenses/Budget

I will not require outside funding for this project.

J. References

[1] Tsonis, A. A., and J. B. Elsner. "Chaos, strange attractors, and weather." *Bulletin of the American Meteorological Society* 70, no. 1 (1989): 14-23.

[2] Newman, David V. "Emergence and strange attractors." *Philosophy of Science* (1996): 245-261.

[3] Manson, Steven M. "Simplifying complexity: a review of complexity theory." *Geoforum* 32, no. 3 (2001): 405-414.

[4] Reynolds, Craig W. "Flocks, herds and schools: A distributed behavioral model." *ACM SIGGRAPH computer graphics* 21, no. 4 (1987): 25-34.

[5] Vicsek, Tamás, András Czirók, Eshel Ben-Jacob, Inon Cohen, and Ofer Shochet. "Novel type of phase transition in a system of self-driven particles." *Physical review letters* 75, no. 6 (1995): 1226-1229.

[6] Krueger, Wesley, "Holistic solution methods for complex multi-particle systems." Senior thesis, Brigham Young University, 2010.

[7] Berrondo, Manuel, and Wesley, Krueger. "The role of consensus and frustration in the emergence of flocking behavior." *UASAL J* 85 (2008): 219-232.

[8] Berrondo, Manuel, and Mario Sandoval. "Defining emergence: Learning from flock behavior." *Complexity* (2015).