Statement of Research Interests

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I first got introduced to research when I was an undergraduate, with Professor Sven Sigurðsson and the late Professor Kjartan G. Magnússon at the University of Iceland. I programmed and simulated a model for the migration of the Icelandic capelin (*Mallotus villosus*) [1], which is a small pelagic fish in the Icelandic waters [2, 3], briefly discussed below. During my graduate studies, with Professor Björn Birnir as my advisor, I worked on similar models and focused on applications to the Icelandic capelin [4]. In addition to models on the migration path of the capelin, I worked on a model on the inner energy fluxes of the capelin, capturing e.g. the roe and fat contents [5]. After graduating, my collaboration with my advisors has continued, and I am also building a network of collaborators around the world [6].

In 2010, I was awarded the UCM-EEA Abel Grant to work with Professor Ana Carpio at Universidad Complutense de Madrid, Spain. My work in Madrid got me involved in very different models than I had previously worked with. These were models of bacteria growing on surfaces with fluid flow; including such mechanisms as cell erosion and decay, cell division, and attachment of suspended bacteria to the biofilm. My collaboration with Professor Carpio, and her doctoral student, David Rodriguez, was both very pleasant and fruitful [7, 8].

I have been very fortunate with both advisors and projects. I was exposed to research during my undergraduate, and I wish to do the same for other students. I enjoy doing research, and hope to produce good work in the coming years. My research interests and goals, along with a brief description of the models used in my research, are discussed below.

1 Interacting particle models

Movements of living organisms have for centuries fascinated their observers. In recent years, much effort has been devoted to answer the question of what drives the complex behavior and patterns exhibited by organisms [9, 10, 11]. Flocks of birds [12, 13, 14], swarms of locust [15], a cluster of bacteria [16] and fish schools [17, 18, 19, 20] are examples of such organisms and behaviors.

Although these systems of individuals can be very complex, the key observation is that the individuals are all very similar, have the same desires and needs, and all follow the same behavioral cues. This results in collective behavior and a group of animals can seem to move as a whole. Interacting particle systems are therefore frequently used to model such behavior [9, 21, 22, 23, 24, 20]. These models are preferred by many biologists because of their discrete nature, but mathematically they are also of great interest. Visually, they have also been used to generate computer graphics of animal movements [12].

The model I used to describe the movements of the Icelandic capelin is based on the models presented in [17, 18, 25] as well as [1, 26]. It consists of N particles in an off-lattice region. We follow [17] by employing three sensory zones around each particle to determine its reaction to the particles around it. This allows the particles to move together as a group. Another important extension to previous models is the additional condition that the particles adjust their speeds to their neighbors, which was added by Hubbard *et al.* [26].

The capelin undertakes a great feeding and spawning migration from and to the shores of Iceland. Much research has been carried out on the migration patterns of the capelin,

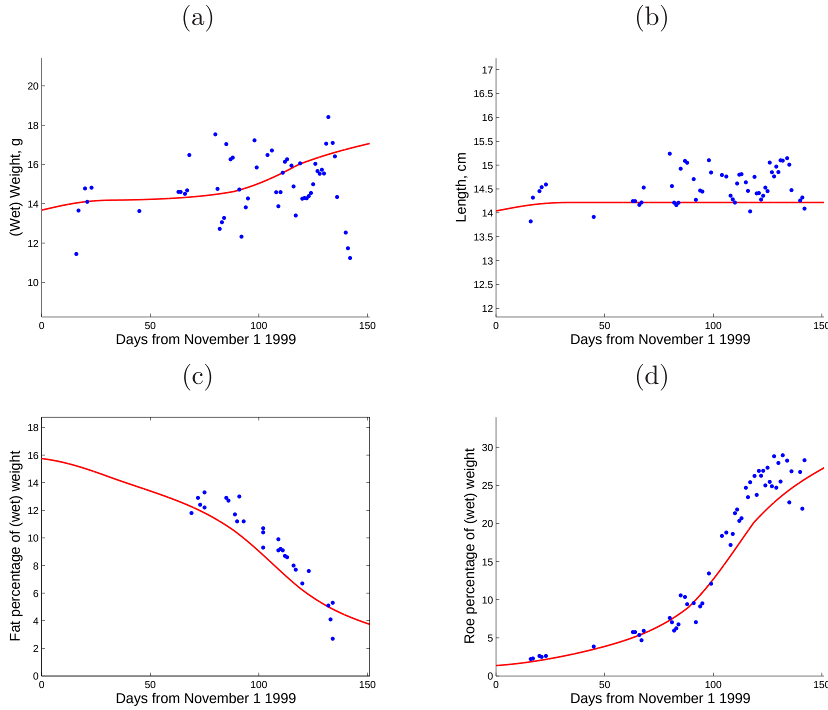

Figure 1: Comparison between measurements (blue dots) and the DEB model (red curves). From [5]. (a) Weight, (b) Length, (c) Fat percentage (d) Roe percentage.

since it is of great importance to the ecosystem and economy [2, 3, 27, 28, 29, 30, 31].

In [4, 32], I worked closely with biologists at the Marine Research Institute of Iceland (MRI), and used temperature data and maps of the currents in the seas around Iceland. By including this environmental information to the model, we were able to recreate the spawning migration of capelin for several years, without using a homing signal. With a sensitivity analysis we showed that there is a very fine balance between how strongly particles sense their environment and how they sense their neighbors. Another interesting result is how a proportionally small environmental sensing is required, compared to the interactions, in order for the whole school to effectively utilize the environmental information.

2 Dynamic Energy Budget Model

Roe maturity has been found to play an important role in the migration of capelin [2]. Dynamic Energy Budget theory (DEB) [33, 34, 35, 36, 37] is the study of the mechanisms of acquisition and use of energy by individuals, that has consequences in physiological organization and the dynamics of populations and ecosystems. It is closely related to bioenergetics that focuses on molecular aspects and metabolic pathways in a thermodynamic setting. DEB theory treats individuals as nonlinear dynamical systems that follow predictable patterns during their life cycle. Recently, the DEB has been used to describe the full life cycle of anchovy [38] and myxobacteria [39].

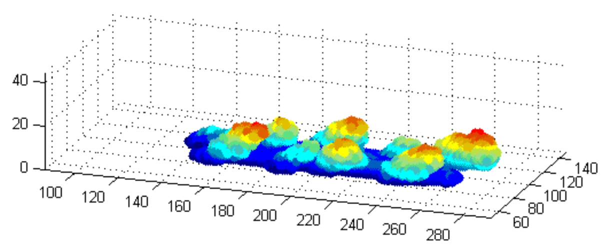

Figure 2: An instance of the 3-d model of the biofilm evolution. From [8].

I have developed the DEB theory to fit the capelin and proposed a new equation to represent the energy contained in roe, published in [5]. Shown in Figure 1 is the comparison between the DEB model and data on weight, length, roe content and fat content of the capelin.

In my PhD thesis, I proposed how to integrate the DEB model with the migration model. The DEB theory will be used to determine certain triggers for the behavior of the capelin based on its roe content and internal energy. With a more biologically accurate model, we will have a better picture of the migration path of the capelin, but more importantly, the timing of the migration. A paper with the proposed model and numerical results is in preparation [40]. We expect to have a good working model which can be used to predict the whereabouts of the Icelandic capelin and compare with acoustic data.

3 Cellular automata models for biofilm growth

From October 2010 through May 2011 I worked with Professor Ana Carpio at the Universidad Complutense de Madrid, Spain. I developed and programmed a 2-dimensional cellular automata model for biofilm growth, see [7]. The model extended the one in [41], by adding the effects of surface flow to the model. This model reproduced observed patterns in biofilm, such as thin layers, streamers, rolling waves, and “mushroom” patterns. Next, I further extended the model to 3 dimensions in a rectangular tube, see Figure 2 [8]. In the 3-dimensional code, the flow is in the direction of the positive x-axis. The 3-d code was designed to naturally extend the 2-d code, where an x-z cross section corresponded to the 2-d model.

Experiments were conducted on bacteria (*Psudomonas putida*) in a rectangular plexiglass tube, by David Rodriguez, to which we compared the model simulations. We actively presented our results in conferences [42, 43]. I am very excited about contining researching models for biofilm growth, in particular finding parameters specific to the *Psudomonas* *putida*. In particular, we wish to investigate if our model can reproduce similar patterns of those described in [44], where bacteria form specific elongated clusters around corners.

4 Other future research goals

4.1 Interacting particle models

I want to derive both the temporal limit of the interacting particle model described above, as well as the limit $N \to \infty$. In the former case, [45] has derived such a limit, but without capturing some of the behavior of the discrete system. We suspect that this discrepancy comes from the fact that the radii of interaction have to be scaled accordingly. When working with interacting particle systems, it is of great importance, both computationally and theoretically, to know how the parameters and the number of particles affect the behavior of the system. In [4], we presented arguments for how parameters should scale in order to maintain the behavior of the system throughout simulations, which I am currently working on verifying [46].

I also want to investigate how information propagates through a school of particles. The speed and efficiency of such propagation, could possibly be analyzed using tools from graph theory, e.g. connectivity of a graph. Connections to work done on networks could also be applied, see [47] and references therein.

4.2 Coupled oscillators

After attending the conference "Swarming by nature and by design" at IPAM in 2006 I became very fascinated with the model of Kuramoto for coupled oscillators [48]. The fairly simple model exhibits a phase transition when the interaction strength between individuals exceeds a certain threshold, and the whole system transitions from a completely incoherent state to a partially synchronized state [49, 50, 51]. This phenomenon is widely observed in nature and it turns out that the underlying dynamics of many system are governed by the same equations of the Kuramoto model, e.g. arrays of Josephson junctions [52] and the swinging motion of the Millennium Bridge in London [53, 54, 55].

I am interested in working on finding the connection between the Kuramoto model and the swarm of a school of fish. Although the Kuramoto model assumes a mean field connectivity between individuals, I believe that a certain density of particles is required for the system to locally behave like the Kuramoto model. We therefore suspect that the interacting particle model above will exhibit similar behavior.

I also wish to investigate stability of solutions of several populations of coupled oscillators. The Kuramoto model has many interesting open problems as well as extensions [56] which I hope to further research. External forcing, time-varying coupling and populations of oscillators have been proposed [57, 58, 59]. I intend to investigate stability of partially synchronized solutions to a population of oscillators. Those solutions are relevant because they correspond to several schools of fish and thus I aim to determine the presence of the Kuramoto model in the interacting particle model described above.

5 Conclusion

I desire and expect to broaden my research interests in various directions, some of whom are mentioned above. I believe that one always has the ability to learn new material and it is essential to progress and mental satisfaction in life.

I find the personal aspect to be integral to research. Not only do I enjoy working with other people but I think that the outcome of collaboration is often greater than the sum of its parts. In addition, interdisciplinary collaboration is very important for the advancement of all participating fields. In my case, discussions with biologists and fishermen have given me vital insight into how to model capelin and other fish.

For all the above reasons I have greatly enjoyed conducting research and I have embraced the challenges and hard work. The excitement of discovery is reward enough for the hours of confusion and frustration. I am determined to continue on this path and I look forward to life in academia.

Sincerely,
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