Experimental Soft Matter Physics
Module 2: BZ Waves Lab

Learning Objectives

1. To explore traveling wave phenomena in chemical and biological systems, using the famous Belousov-Zhabotinsky (BZ) reaction as a laboratory model.
2. To appreciate the broader significance of the BZ reaction in the history of nonlinear science, especially the connection between this system and other famous examples of excitability such as the FitzHugh-Nagumo model.
3. To gain additional experience with scientific programming, taking advantage of quantitative image analysis techniques and computational skills developed in previous labs.

Introduction

Oscillating chemical reactions are a beautiful and rich area of interdisciplinary scientific activity. In the 1950s, when Boris Belousov first discovered the reaction that now bears his name, the possibility of oscillatory reaction dynamics was met with widespread skepticism. Everything changed in the 1960s and 1970s, however, as a number of different chemical and biochemical oscillators were discovered, both in laboratory experiments and in a new generation of mathematical models. During this time, further investigation of the BZ reaction uncovered yet another surprise. Usually, the BZ cocktail is stirred continuously to ensure complete mixing of all reactants. In an unstirred environment, however, one finds colorful waves of chemical activity that travel from one part of the solution to another, forming spiral and target patterns. These waves are the subject of this lab.

Oscillations and waves are, from a physics perspective, closely related phenomena. The sinusoidal waves you learn about in classical mechanics and electrodynamics courses, for example, can be thought of as a spatially organized form of simple harmonic oscillation. Unlike mechanical and electromagnetic waves, however, the chemical waves generated by the BZ reaction cannot be superimposed. When two BZ wavefronts meet they simply extinguish one another. While this may seem perplexing, we have already encountered something similar earlier this semester. An excited neuron, you'll recall, cannot initiate another action potential until after it returns to its rest state and, as a result, action potentials never travel backwards or pass through one another. There is, in fact, a deep connection between these systems: the BZ reaction, like neurons, is capable of excitable dynamics as well as oscillation. In this lab, after analyzing photographic evidence of chemical waves, you will explore this connection.

Experimental Perspectives

As you'll remember from last week's lab and reading materials, major ingredients in the classic BZ reaction recipe include a source of bromate and bromide ions, malonic acid, and metal ions that serve as a catalyst. This week, we'll be using a slightly different recipe featuring these same ingredients. We'll need the following stock solutions:

Solution A: Dissolve 3.772 g of sodium bromate in 50 mL of ultra-pure water. (This creates 50 mL of 0.500 M $NaBrO_3$ solution.)

Solution B: Add 16 mL of sulfuric acid to 34 mL of ultra-pure water. (This creates 50 mL of 6.00 M sulfuric acid.)

Solution C: Dissolve 2.572 g of sodium bromide in 50 mL of ultra-pure water. (This creates 50 mL of 0.500 M NaBr solution.)

Solution D: Dissolve 2.602 g of malonic acid in 50 mL of ultra-pure water. (This creates 50 mL a 0.500 M malonic acid solution.)

To initiate the reaction, combine 6.0 mL of solution A, 0.6 mL of the sulfuric acid (solution B), 1.0 mL of of solution C, and 2.5 mL of of solution D in a separate beaker. Swish this mixture until the color changes from amber back to clear. (Again, this brownish color is associated with the formation of poisonous bromine gas, so it's important to use a chemical fume hood when initiating the reaction.) To initiate waves add 1.0 mL ferroin, swish again, and pour into a small petri dish.

This semester, due to the impossibility of maintaining adequate social distancing in departmental laboratory spaces, we will not be directly observing these wave patterns together. We will instead be working with photographs taken by previous generations of Colby physics majors. These photographs were taken at a fixed rate of 2 images every second in a darkened laboratory. A small piece of silver was placed at the center of the dish, generating a target pattern of outward traveling wavefronts. Using diffuse blue light to illuminate the dish causes red and blue phases of the BZ reaction to show up as dark and bright regions, respectively, making the wavefronts easy to capture in black-and-white photographs. Each group will be provided with 1200 photographs to analyze. If you create a video from these images, or just simply flip through them rapidly by hand, you'll be able to see the pattern changing.

In last week's lab, you learned how to load and analyze sequences of images using Matlab. This week, your challenge is to take advantage of these skills and use the data to say something quantitative and scientifically meaningful. It may help to envision actual plots that might be interesting, e.g., of intensity as a function of time and/or position. The creation of these plots then becomes your goal, starting with the question of how to extract the relevant quantities from your images. Likewise, it may also help to set these plots aside and simply ask yourself which aspects of the observed data are at all quantifiable. Are there particular observations or observational questions, concerning periods or wavelengths for example, that might be interesting to have data on? If so, these questions can provide focus as well and help guide your analysis. Don?t overcomplicate this process. One or two interesting plots, perhaps supplemented with one or two meaningful numbers, may be enough to tell a good story about the BZ reaction.

For additional historical perspective on the BZ reaction, you could take a look at Zaikin and Zhabotinsky's article in Nature magazine (1970) and Winfree's article in Science magazine (1972), as well as various sources that describe the reaction mechanism and the Oregonator model in more detail. If you're looking for broader perspective about chemical pattern formation more generally, you might take a look at some of the review articles available online (though these can be challenging), as well as Philip Ball's writings on patterns.

Theoretical Perspectives

Last week, we introduced a simple quantitative model of the BZ reaction, now known as the *Oregonator*. Like the Brusselator and several other influential models of chemical or biochemical oscillations discovered in the 1960s and 1970s, the Oregonator model generates a limit cycle in phase space for realistic parameter values. In its simplest form, the Oregonator requires only two coupled differential equations,

$$\epsilon\dot{U} = U(1-U) - fV(U-q)/(U+q), \tag{1}$$

$$\dot{V} = U - V, \tag{2}$$

where U and V are chemical concentrations. (For more details on where these equations come from, if interested, you can consult the original papers and other sources available online.) Solving these equations numerically and interpreting these solutions requires some care. Last week's lab offered Matlab-based tools for this and, using these tools, you can show that system trajectories converge to a limit cycle for some choices of ϵ, f, and q, but for other parameter combinations the trajectories instead converge to a fixed point in phase space.

This week, your challenge is to take advantage of these skills and show that these fixed points can be excitable. That is, like the FitzHugh-Nagumo model and many other excitable systems, the Oregonator can transition between excitable and oscillatory dynamical behaviors as system parameters are changed. Try, for example, looking at the model's behavior for $\epsilon = 10^{-2}$, $f = 3$, and $q = 2 \cdot 10^{-3}$. Other choices work as well. You should be able to confirm that a limit cycle is not present for these values and, using ideas from our excitable systems lab, confirm that the steady state is indeed excitable. (Try to assemble a visually appealing and convincing argument!) To go deeper, you might also explore the connection between this model and the much simpler-looking FitzHugh-Nagumo model. Additional reading about both models, or about excitable systems more generally, might provide some helpful intuition or inspiration. The literature on pattern formation in excitable systems is quite interesting and has grown considerably since the 1970s.