Personal, Background, and Future Goals Statement

I have an *affaire de coeur* with practical problem solving. Shortly after my college debut at Montana State University, I was briefly involved in a collaborative effort to analyze the vast expanse of data collected by the Greenbank Observatory in hopes of identifying new pulsars. This was my first exposure to computational mathematics, the basis of modern practical problem solving, and I knew I wanted to explore the field deeper. Eventually, I ended up in a more permanent position with Dr. Brian D'Urso. Here, I expanded my adeptness in computer systems, experimental physics, and research in general. At the conclusion of my work in the Department of Physics, I began working with Dr. Dominique Zosso in the Department of Mathematical Sciences. In this new environment, I applied and further broadened my skills in software development, research, and mathematical dissemination, as well as imbibed the sea of mathematical topics my colleagues had delved into. This is where I truly found a passion, a passion that demanded I pursue higher education to further hone my skills.

I am currently a first year graduate student at Montana State University seeking a master's degree in mathematics. Continuing my journey with Dr. Zosso, I plan to compose a thesis covering my proposed project on deep learning of partial differential equations (PDEs). This accomplishment will serve as the dress rehearsal, before I take the live stage pursuing a doctorate in mathematics. Looking further into the future, I see myself applying my mathematical, and computational utensils to a career in solving practical problems. I also see myself as a clear, concise, and confident mathematical interpreter, capable of presenting my work to any appropriate audience. However, in the interim, I will continue my studies and research to hone my skills required to ultimately obtain these goals.

Intellectual Merit

I am particularly well suited for my proposed research in deep learning of PDEs due to my <u>broad experience in developing software for scientific purposes</u>. Dr. D'Urso's research group focused on microsphere (particle) trapping and precision measurements. Throughout the experiments, we trapped particles in vacuum and took measurements of their oscillation [1]. Then, we would attempt to damp their oscillation with an active feedback system. The use of high-speed computation was paramount, as these dynamic measurements were made in micrometers and Megahertz. Many of the optics used in the experiment required fine adjustments throughout a measurement. Small changes in environmental conditions caused the particle to shift position in the trap; this moved the particle out of range of the detector. Manual adjustment was not a practical or robust solution; hence <u>I independently developed a program to interface with several electronically controlled mirrors</u> that took an input from the detector, and then dynamically adjusted the mirrors to where the particle was centered on the detector. While this could have been accomplished with an analogue circuit, the program allowed for simpler calibration and manual input, which proved invaluable for initial alignment.

The active feedback system in the experiment took an output from the detector, and sent a signal to several electro-optic modulators (EOMs); in short, these instruments split a laser beam, and allowed us to damp the motion of the particle via scattering. This scattering corresponded to a momentum exchange between the particle and each beam of the EOMs. For example, when the particle moved to the left, the EOM damping left-right motion would increase the left beam's power, and decrease the right beam's power imparting a net force on the particle to the right. Due to the geometry of the trap, we were unable to send these beams at the optimal angle, thus the beams tended to bias the particle away from the stable point in the trap. We theorized this limited our ability to damp the motion of the particle. To address this, I independently developed a program that would interface with the EOMs and would bias the particle in the direction of the users choosing. We found that when the particle was biased near the stable point in the trap, our cooling performance was substantially improved.

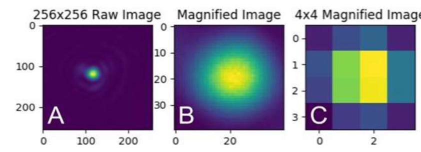

Figure 1: All images depict the trapped particle. **(A)** Unaltered frame taken by the camera. **(B)** Simulated magnification of frame. **(C)** Simulated image from 4x4 photodiode array.

The detector we used in the experiment was initially a two-by-two photodiode array. This detector was cumbersome to calibrate, and yielded poor resolution of the particle's motion in the direction towards and away from the objective lens. This led us to use a camera in place of the two-by-two detector. The camera provided excellent resolution; however, our damping ability was diminished substantially. At top performance, the camera produced damping an order of magnitude worse than the two-by-two detector, likely due to digital noise. Dr. D'Urso identified a unique four-by-four detector that could provide improved resolution over the two-by-two detector, whilst simultaneously yielding superior damping over the camera. Due to the time and cost required to implement a new detector, we needed to know whether this detector would in fact provide satisfactory resolution prior to purchase. To test if this detector could achieve acceptable resolution, I independently created a simulation that would compare the signal detected by the camera to the signal detected by the four-by-four photodiode array. To accomplish this, I drew data from the camera, then devised and implemented a scheme that would reshape the data, see Figure 1, into a form that would be representative of the four-by-four detector output. After I performed Fourier analysis on both the camera data, and the simulated data, see Figure 2, I found strong cross-correlation between both signals. Accordingly, the lab purchased the new detector. At the conclusion of this project, I transferred to Dr. Zosso's group.

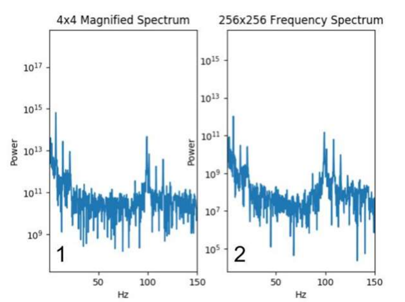

Figure 2: These spectrums are each of the same set of frames. The peaks near 8Hz, 94 Hz, and 100 Hz are the frequency of particle oscillation in each direction. **(1)** The spectrum of the simulated 4x4 photodiode array. **(2)** The spectrum of the unaltered camera frames.

One of the projects Dr. Zosso pitched to me involved collaboration with the Department of Microbiology Immunology. Efficient and robust computational methods in the medical field is vital. Hence, the opportunity to assist in this project was alluring. Dr. Diane Bimczok and her team of biologists analyzed human stomach tissues and attempted to determine whether dendritic cells (DCs) were randomly distributed throughout the tissues, and whether **H.** *pylori* infections altered this distribution [2]. Catherine Potts, a graduate student in Dr. Zosso's group, had developed an image processing pipeline for locating the DCs, and Jordan Love, an undergraduate, had developed a statistical pipeline that would calculate several spatial statistics of the located DCs. This statistical pipeline also had the capability of creating a Monte-Carlo simulation of randomly distributed Dcs, see Figure 3, that the real data could be compared with. These two pipelines had limited function. The image processing pipeline could not be easily run by the

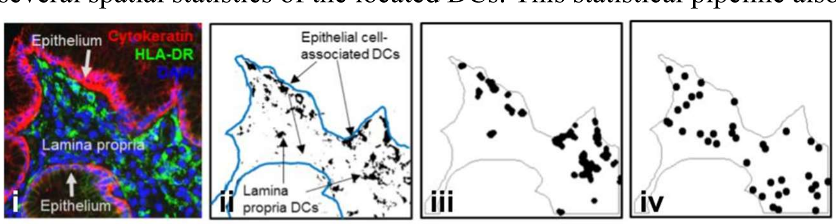

Figure 3: Analysis of DC distribution in the gastric mucosa. **(i)** Digital image of a gastric tissue section: epithelial cells (red), DCs (green), and nuclei (blue). **(ii)** Thresholded DC image with epithelial trace. **(iii)** DC distribution as point pattern. **(iv)** Monte Carlo model.

biologists. This made determining the accuracy of the pipeline difficult on an administrative level. The pipeline also suffered from lack of robustness; inconsistencies in the images of the tissues yielded inconsistent results. The statistical pipeline suffered from similar problems; we later decided the output of the statistical pipeline should also be changed. To address these issues, I collaboratively developed and deployed user-friendly software that addressed these deficiencies, streamlining and making the process more robust. The results of this project could lead to new understanding of interaction between the passive and active immune system.

Broader Impacts

In conjunction with performing research, I strive to be an active member of the mathematical community. I frequent seminars where other mathematicians disseminate their research and try to absorb as much as possible from them. I gave a presentation on the interdepartmental biology project at the Data Science and Image Analysis Conference of the Pacific Northwest, and engaged in productive conversations regarding steps to further improve the project with other conference constituents. This setting required a high level dissemination of the methods used in the project to effectively convey the importance, and impacts of the project to the audience, composed of people working in similar fields. I also presented my research on the biology collaboration at Montana State University's Winter research celebration. This is an annual, campus-wide event where students present their research. This environment brought many people who were not versed in mathematics or biology to my project, and the experience helped me to communicate the ideas of the project more thoroughly. Mathematical dissemination to individuals not in the field is paramount to practical problem solving. In the collaborative project with the Dr. Bimczok's team, our ability to effectively communicate with each other led to the creation of a simple-to-use and effective program that has proved instrumental in realizing the goals of the project. I am currently a graduate teaching assistant for a lower division class. the majority of my students will not continue on into a mathematical career; however, my experience in assisting them through the course has shown me areas where I can improve my ability to effectively communicate the material. These experiences have helped me in the pursuit of my goal of becoming a clear, concise, and confident mathematical interpreter.

My immediate goals are to continue working with Dr. Zosso's group, publishing a paper on the collaborative project with Dr. Bimczok's team, and delving deeper into the proposed project of machine learning of PDEs. The ability to solve a PDE, particularly a complex, or high-dimensional PDE, with less computation time and error has implications in a vast array of areas including physics, biology, finance, and computational mathematics. Throughout my career, I will remain an active member in the mathematical community, and continue to learn, grow, and share my experiences for the amelioration of the community.

References

[1] Bradley R Slezak, Charles W Lewandowski, Jen-Feng Hsu, and Brian D'Urso. "Cooling the motion of a silica microsphere in a magneto-gravitational trap in ultra-high vacuum." *New Journal of physics*, 2018.

[2] D Bimczok, RH Clements, KB Waites, L Novak, DE Eckhoff, PJ Mannon, Smith PD, and Smythies LE. "Human primary gastric dendritic cells induce a th1 response to h. pylori." *Nature (MucosalImmunology)*, 2010.