"Just keep swimming."

Dory, *Finding Nemo*

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Conclusion

In this thesis, we have explored three facets of fluid–structure interaction (FSI): one-way coupling between rigid solids and fluids, two-way coupling between deformable solids and fluids, and artistic patterning of fluids with solids. In Chapter 2, we developed `cryoflo` for three-dimensional simulations of sample vitrification in cryo-plunging. In Chapter 3, we introduced the LBRMT for simulating multi-body interactions between soft solids and fluids. In Chapter 4, we explored the ancient art form of marbling and proposed a basic formulation of marbling simulation. A common theme is the development of multiphysics simulation to study complex physical phenomena and provide insights that are difficult to obtain through theory or experiment alone.

We have outlined future directions for each chapter in the respective discussion sections. For the development of multiphysics simulation as a whole, we envision that our computational frameworks can be extended to study problems in active matter and biological fluids, as well as innovate new designs for systems that involve fluids, solids, and other physical phenomena, such as redox flow battery [272] and programmable metafluids [273]. However, we recognize the importance of continuing the development of these tools and making them more generalizable. In fact, most simulations developed for one particular research project often stay within the project. Even with amazing work, they are either limited to specific problems or lack maintenance and further development. A few stellar examples have stepped outside this conundrum and become important tools to aid in new scientific discovery, engineering design, and physical understanding, such as `Voro++` [274, 275], `LAMMPS` [276, 277], and `SINDy` [278, 279]. The amount of maintenance and extension required to make research code user-friendly and generalizable is often underestimated, but it can be rewarding. We intend to continue the code development of `cryoflo`, `LBRMT`, and `marbling-fluids`, making them available to the community to be used and extended to simulate more physics and solve more problems.

From reduced-order models to full-physics simulations [280], computational methods—highlighted by the development of "digital twins" for domain science—have been prevalent in scientific discovery since the mid-twentieth century. Currently, we are witnessing a shift towards a data-driven era [281]. Successes in simulating these forward problems not only serve as reliable datasets but also bring opportunities to tackle inverse problems like optimization and design [15]. One approach to solving inverse problems is via automatic differentiation, as seen in differentiable molecular dynamics [282], unsteady turbulent flow [283] and mechanical metamaterials [284]. A differentiable multiphysics FSI simulation can provide a new way to understand the two-way coupling and potentially a new paradigm for designing and optimizing shape, material, or flow with biological and engineering applications.

Here feels like a good place to drop the "royal we" and use a singular pronoun to conclude my thesis. My journey into fluid–structure interaction actually started with animated movies. I have always been an avid animation lover. The reason I chose to attend graduate school in the first place was because I found the existence of physics-based animation and I wanted to learn about it. The past six years have been a fantastic journey. I have learned about numerical methods for computational physics, watched many animated movies, and interned at both game and animation studios. It seems I was close to realizing what I wrote in my PhD application statement of purpose: one day to see my name rolling down in the end credits of animated movies. But this love for animation has grown beyond itself. Understanding and visualizing the physics of the world we live in has its unique charm and merit. There are many unanswered intriguing questions in FSI, and I aspire to combine simulations with animation to share with the world the excitement and beauty of fluids, solids, and their interactions.

"Just keep swimming."