Senior Honors Project Proposal

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Proposal and Objectives

Infills are the 3D printed structures inside of solid objects that provide support and increase durability. Given an arbitrary 3D object and a corresponding set of desired physical properties, what is the optimal infill structure and how can we generate it? Specifically, the set of physical properties that I am interested in consist of structural integrity against three types of stress: compression, tension, and shear.

Currently, a large majority of 3D printed objects can fit on the palm of one's hand and they only use infills as structural support against gravity. However, the field of 3D printing is expanding and developing rapidly. With the advent of Big Area Additive Manufacturing (BAAM), volume and weight will soon become an important consideration of large-scale 3D printed objects. In addition, as 3D printed objects begin to serve more roles than desk ornaments and are used in other practical applications, their structural properties will also become a consideration. Thus, there will be an increased demand for infills that are lightweight yet strong enough to fulfill structural roles.

A possible way to generate optimal infill structures would be through the application of sphere packing, a field in geometry concerning the fitting of spheres into a closed shape or dense lattice. Sphere packing can create infill structures as well as provide the ability to locally manipulate the structures based on modifying factors such as stress. For example, if we wanted to 3D print a robotic arm and we know that the arm will experience greater stress at the joints, then we could modify the infill structure so that it can withstand greater stress in those parts specifically without increasing the infill density of the entire arm and adding unnecessary weight. These procedures will be explained in more detail in the tentative outline section. To summarize, my work will consist of creating sphere packing software that takes in a 3D object and through a series of stages generate an optimal 3D infill structure.

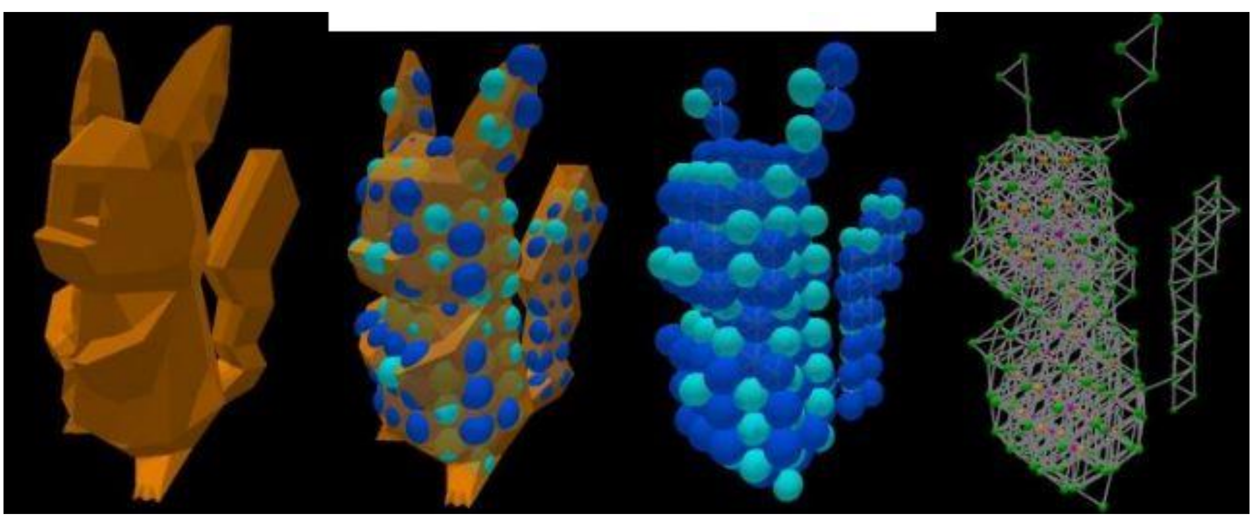

Figure 1: Example photos of the sphere packing process.

Review of Literature

A sphere packing of a 3D object consists of the maximum number of spheres of a given radius that can fit inside the object without overlapping each other. The packing density of a sphere packing is defined as the ratio of a volume occupied by the spheres. In 1611, Kepler conjectured that the face-centered cubic and hexagonal close-packed lattices have the highest packing density (0.74048) for all sphere packings of spheres of equal sizes (Conway & Sloane, 1993; Steinhaus, 1999). Gauss proved in 1831 that this was indeed true for the lattice subset of sphere packings, but it was not until 2014 that Thomas Callister Hales proved it was true for all sphere packings (Hales, Solovyev, & Hoang, 2014; Conway & Sloane, 1993). On the other hand, the sphere packings I will be working with consist of packings of spheres of many different sizes. There exists literature describing dense packings of two sphere sizes, but there is sparse literature involving packings of more than two sphere sizes. However, we are less concerned with the packing density aspect since we are mainly interested in the contact graph corresponding to each sphere packing. The contact graph has vertices at every sphere center and edges between every pair of vertices where the corresponding spheres are tangent. The contact graph is important because it becomes the infill structure that we are trying to generate.

Since optimizing structural integrity of the infill structure is a major goal of this project, I also need to consider structural mechanics with a focus on computation of stress within structures. My preliminary research on existing methodology for designing structures to resist stress indicates that most of such structures have been developed throughout human history through empirical methods. Only after the necessary scientific and mathematical foundations were invented in the 17th and 18th centuries did we begin obtaining ways to model stresses. One of the earliest, well-defined mathematical models of stress was devised by Augustin-Louis Cauchy in the 19th century (Adeeb, 2017). This model uses a second order tensor to completely define all stresses at a point inside a material subjected to forces (Adeeb, 2017). Today there are many software tools that can compute stresses using a wide variety of models including the aforementioned one. Although there are tools to calculate stresses on objects given material properties, object geometry, and applied forces, there are no readily available ways to augment complex graph-based structures to counter stress aside from material alteration. Thus, the procedures for creating and refining the infill structures must be designed *de novo*. Following the conventions established by the experts, I will use modeling software to run simulations first for convenience, but then I will aim to validate the properties of the generated infill structures empirically.

Given that the goal of the project is to generate new infill structures, it would be pertinent to first explore existing infill structures and their characteristics. Existing infill structures are generally uniform with some examples being linear, diagonal, and honeycomb infills. There are not very many studies on infill structures since 3D printing is a relatively recent development; however, I came across two studies that provided notable characterizations of infill structures.

A study on 3D printed polylactide, which is a thermoplastic polyester also known as PLA, was conducted by a 3D printing research company to quantify the impact of different printing parameters on performance (3D Matter Inc., 2015). The performance was evaluated in terms of max stress (ultimate tensile strength), elongation at break, and printing speed among other factors. A seemingly trivial but nevertheless essential result to note was that strength increased as infill percentage was increased (3D Matter Inc., 2015). Another important result was that the decorative infills, Moroccan stars and Catfill, were weaker than the structural infills (3D Matter Inc., 2015). One last result to note was that the 90% infill consistently had less elongation at break and greater yield stress than infills below 80% as well as 100% (solid) infill (3D Matter Inc., 2015). They hypothesized that the air voids in the non-solid infills behave as faults that localize the stress and thus at a macro level the 90% infill outperforms the 100% infill.

A different study that used acrylonitrile butadiene styrene, which is a thermoplastic polymer often abbreviated as ABS, instead of PLA found that honeycomb infill patterns were only slightly stronger (<5%) than other infill patterns and that infill density determines mainly tensile strength (Miguel, Wilson, Santiago, & Andres, 2016). Also, like the other study, they found that air voids in the infill altered mechanical properties (Miguel et al., 2016). In addition, they found that the angle of the infill structure can affect whether the 3D printed object is brittle or ductile (Miguel et al., 2016).

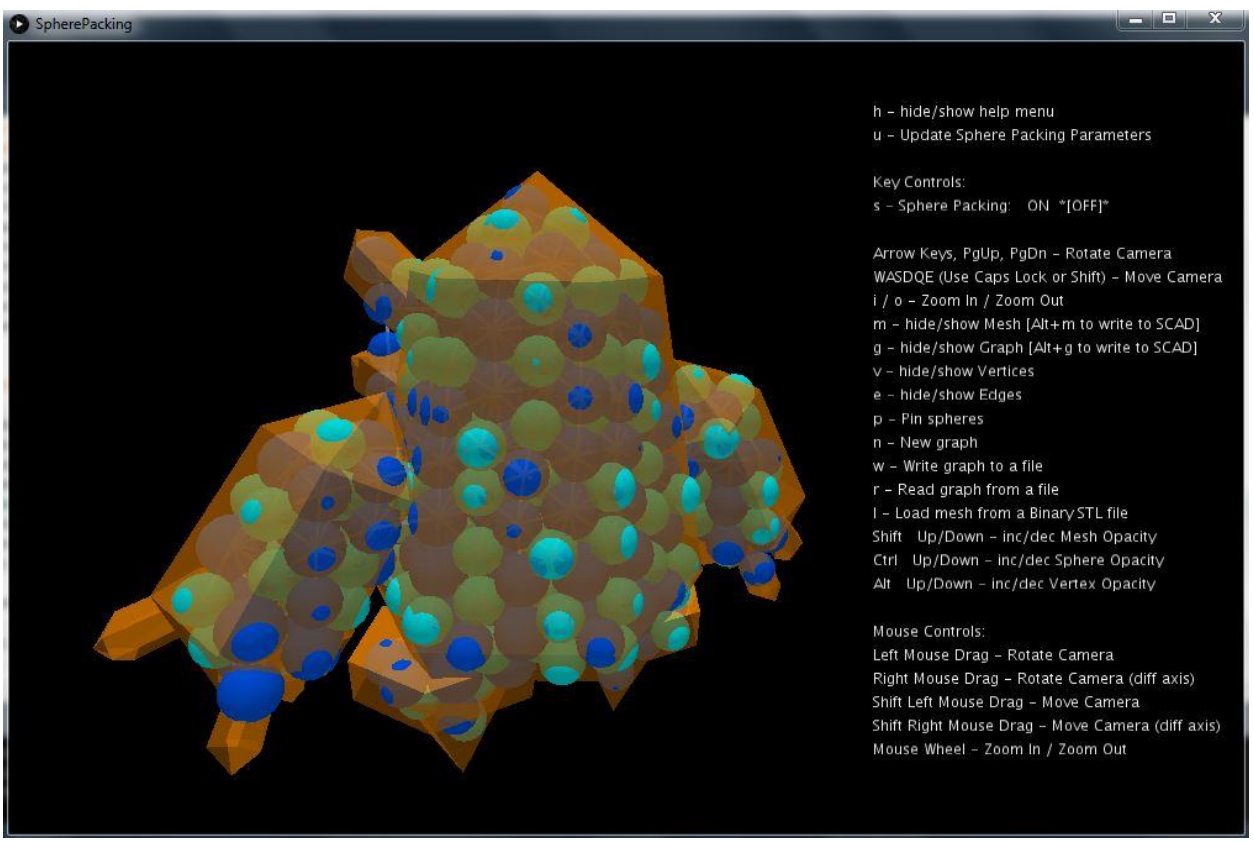

Figure 2: Screen shot of my sphere packing software.

Tentative Outline

Phase 1 – Infill Structure Generation

0. I will first need to familiarize myself with the Processing Integrated Development Environment (IDE), which is the software development tool I will use to create the sphere packing software. I am choosing Processing because it abstracts away the messy details of graphics programming so that I can focus on the higher-level aspects of the software I am creating.
1. I will design and create the data structures for the geometric, graphics, and graph primitives.
2. I will implement code to render all the visual elements.
3. I will implement view controls so that the user can better visualize and interact with the 3D sphere packing model and graph model.
4. I will create methods to generate initial cubic lattices and hexagonal close packed lattices.
5. I will implement a STL file loader method to read in all the triangles from a STL file and create a mesh that represents the 3D object. STL stands for stereolithography and it specifies a file format for describing the triangulated surface of a 3D object.
6. I will implement a method to generate an initial lattice graph inside of a given STL object.

   Note: The graphs are contact graphs of sphere packings. Also, the vertices of the graphs have a 3D embedding through a bijective mapping to spheres in the sphere packing and the edges of the graph are dual to sphere tangencies. The dual nature of the graph and sphere packing will provide a unique setup where I can manipulate the graph and automatically fit the graph inside the object at the same time. The usefulness of this setup is that we can selectively edit the structure at a local level. This enables the creation of specialized infill structures that are not constrained to be uniform.
7. I will implement an algorithm for sphere packing that is based off a circle packing algorithm designed by Dr. John Bowers. This algorithm applies an iterative method to increasingly fit an initial lattice to the inside of a 3D object.
8. I will implement sphere packing controls so that the user can alter the sphere packing parameters at run-time. These controls will be updated as new parameters are added to the sphere packing algorithm.
9. I will implement the interface help menu so that the user knows what the controls are. The help menu will be updated as new user-interactive functionality is added.
10. I will design a file format and implement file IO functionality to enable storage of sphere packing graphs in a non-volatile form.

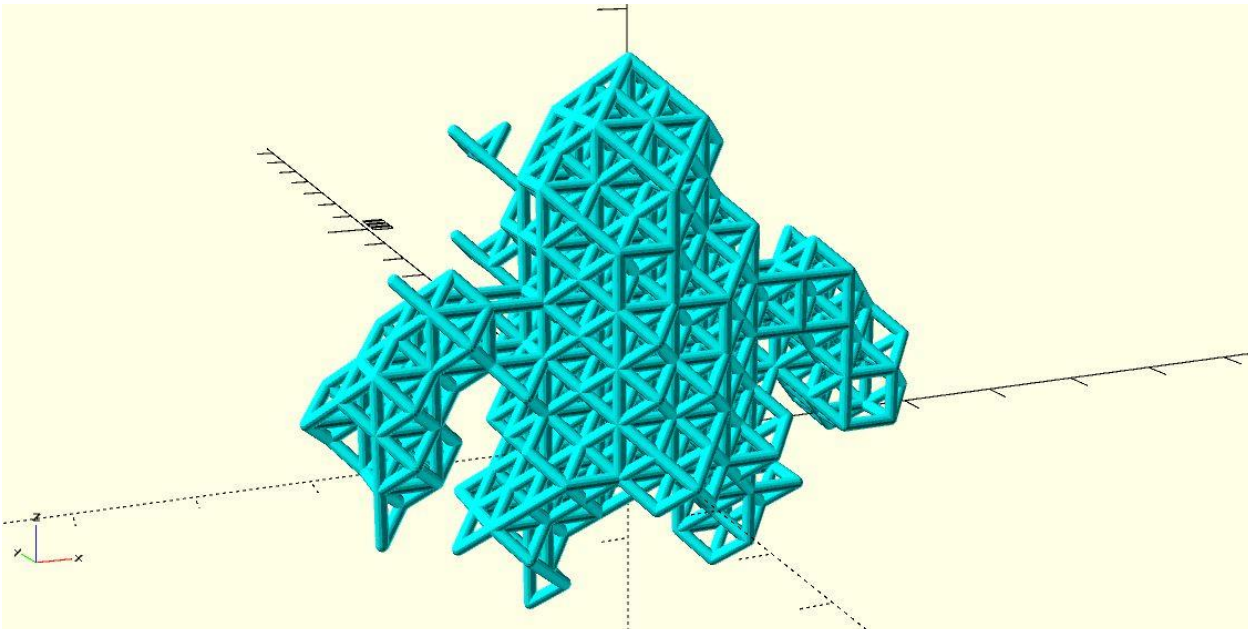

Figure 3: Solid form of graph created using OpenSCAD.

Phase 2 – Infill Structure Refinement

0. I first need to learn OpenSCAD, which is the software I will be using to convert meshes to solid form.
1. I will write an OpenSCAD script that converts graph (infill structure) output from sphere packing into a solid in the form of a STL file so that it can be printed.
2. I will test print the infill structures which can be sliced with any 3D slicer program (including open-source ones) and printed on any existing 3D printer. This step is done for a sanity check. Specifically, I'll probably use Dr. Bower's 3D printer.
3. I will find and utilize suitable software for application of forces on 3D objects to calculate stresses on specific nodes of a graph. This software can be open-source like FreeCAD's FEM module or it can be high-end commercial software like COMSOL.
4. I will implement at least one refinement algorithm that takes in the original 3D object, the current sphere packing graph, and stress data and then outputs a refined graph.
5. I will design and generate experimental structures to test for structural integrity based on available physical tools. I will either work with a physics professor on this or I may contact some personal connections for help.
6. I will print all the objects I need to test.
7. I will perform mechanical stress tests on all the objects and record all necessary data.
8. I will then analyze the data.
9. Steps 4 through 8 may be repeated if appropriate.
10. At the end, I will draw conclusions based on my analysis.

Intended Learning Outcomes

Upon successful completion of this project, I will have gained extensive experience in both research, software development, and the scientific process. Furthermore, I will have explored a subject area which is not taught in the normal curriculum. Lastly, I will have learned how to apply interdisciplinary knowledge to solve a real-world problem.

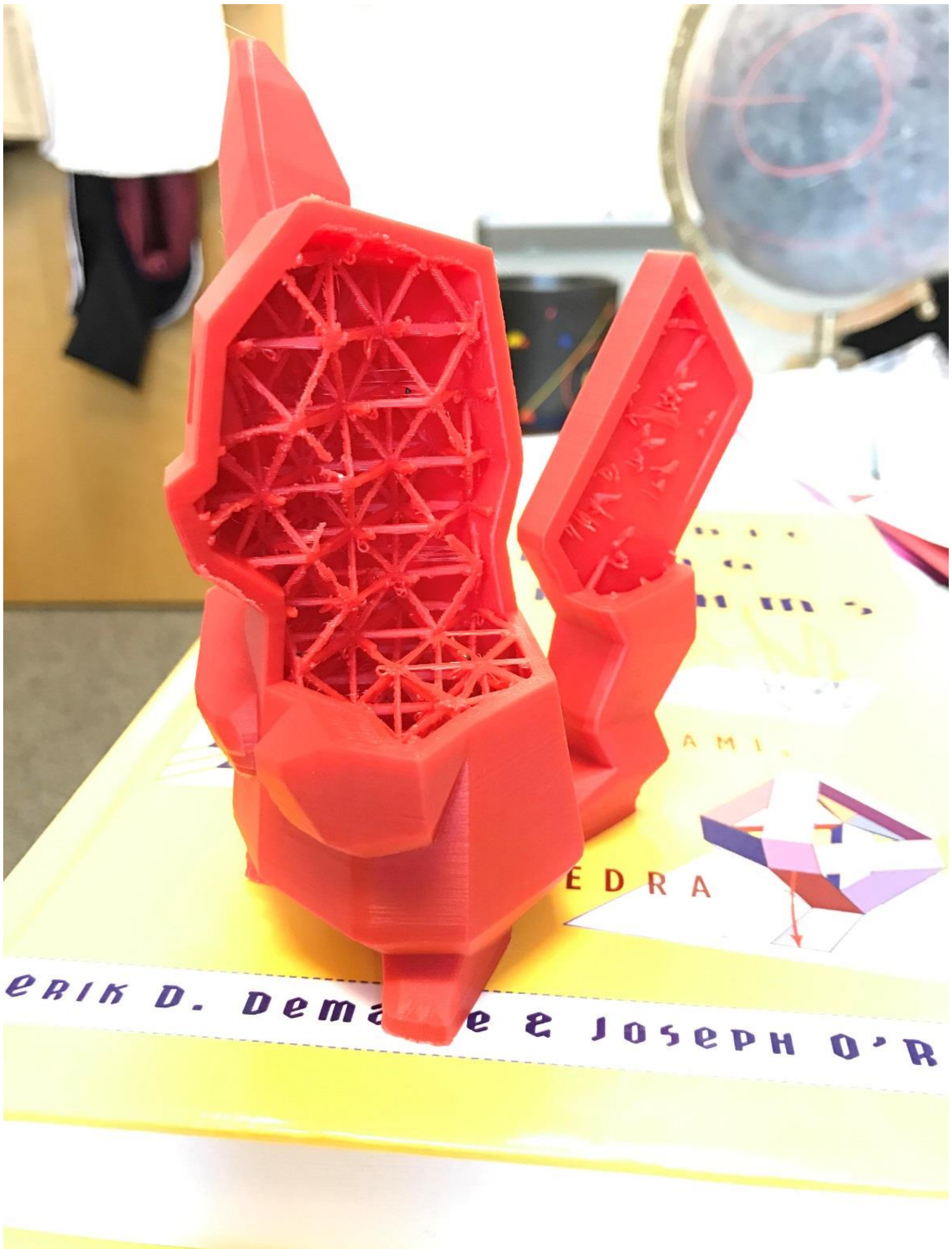

Figure 4: 3D Print using infill structure generated by sphere packing.

Hypotheses

If two 3D printed cylindrical objects have the same mass with one being a hollow shell and another being pure infill without a shell, then the infill structure will withstand greater compression, tension, and shear stress.

If two 3D printed cylindrical objects have the same mass with one using a uniform diagonal grid infill and another using my sphere packing infill, then my sphere packing infill will withstand greater compression, tension, and shear stress.

If two 3D printed bridge trusses have the same mass with one using a uniform diagonal grid infill and another using my sphere packing infill, then my sphere packing infill will support a greater maximum load before breaking.

Expected Research Outcomes and Product

If any of my hypotheses are correct, then the outcome of this research will be a new method of generating infill structures that are both lightweight and strong against application of select forces. There will be two products from this project. The first is the sphere packing software program and the second is a thesis paper with experimental results that will be presented to a panel of readers.

Methodology

For this project, I will be employing a modified form of the agile software development framework called Scrum. The framework is modified because I am working alone instead of in a team. Following the Scrum workflow, I will be conducting two week sprints during which I will rapidly prototype and develop new features that are listed in the product backlog. At the beginning of each sprint, I will conduct sprint planning and set up the schedule for completing one or more selected tasks for the next two weeks. After that I will work per the schedule and ask my advisor for advice if I come across any impediments. At the end of each sprint, I will review the work that was done and reflect on how I can improve the process for the next sprint. This methodology is well suited for my project since I may find certain desirable features to be missing or some originally planned features to be less useful as the project progresses. With the fast and flexible approach entailed by Scrum, I can continuously adapt to issues that commonly arise in experimental projects such as this.

Timeline

Prior Work (Fall 2016):

Develop the sphere packing program using Processing IDE to have all the functionalities described in phase 1 of the methods section.

- October 10, 2016: Familiarized myself with the Processing IDE.
- October 17, 2016: Designed and created data structures for geometric, graphics, and graph primitives.
- October 24, 2016: Implemented rendering of all visual elements.
- October 31, 2016: Implemented 3D view controls for user interactivity.
- November 7, 2016: Implemented cubic lattice generators.
- November 14, 2016: Implemented STL file loader to create graphical mesh object for display.
- November 21, 2016: Implemented contained lattice generators.
- December 5, 2016: Implemented sphere packing simulation algorithm.
- December 12, 2016: Implemented sphere packing controls for run-time interaction with sphere packing.
- December 19, 2016: Added user interface help menu to provide instructions on how to use the software.
- December 26, 2016: Designed file formats and implemented file IO for sphere packing graphs.

Current Work (Spring 2017):

Convert graph (infill structure) output from sphere packing software into solids and then test print.

- February 13, 2017: Familiarized myself with OpenSCAD.
- February 20, 2017: Wrote OpenSCAD script to convert graph to solid.
- February 27, 2017: Test printed infill structures generated by sphere packing.
- March 27, 2017: Found a suitable program, COMSOL, to simulate the application of forces to my infill structure.
- April 24, 2017: Familiarize myself with the simulation software.

Future Work (Fall 2017):

Implement refinement algorithm in sphere packing software and conduct experiment to verify that refinement produces the desired physical properties.

- September 25, 2017: Finish implementing refinement algorithm.
- October 2, 2017: Finish designing experimental structures and generate corresponding infill structures.
- October 16, 2017: Finish printing the experimental structures.
- October 30, 2017: Finish testing the experimental structures and recorded all data.
- If refinement unsuccessful
    - Revise refinement algorithm within 1 week
    - Generate and print the experimental structures within 2 weeks
    - Retest the experimental structures within 1 week after Thanksgiving
- Else if time permits
    - Create a different refinement algorithm within 1 week
    - Generate and print the experimental structures within 2 weeks
    - Retest the experimental structures within 1 week after Thanksgiving
- December 11, 2017: Write up report on experiment.

Future Work (Spring 2018):

Write up the thesis paper.

- January 15, 2018: Finish writing up introductory chapter and research chapters.
- January 29, 2018: Finish writing up methodology.
- February 19, 2018: Finish writing up main body of thesis.
- February 26, 2018: Finish writing up concluding chapter.
- March 5, 2018: Finish writing up table of contents.
- March 12, 2018: Finish revising thesis paper and sent thesis paper out to faculty advisor and readers.
- March 26, 2018: Submit final project and thesis to the honors college.
- Late April: Defend thesis.

References

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