Spring June 6th, 2018

Granular Convection and Crystallization of a Two-Dimensional Granular Medium

Donley S. Cormode

Seattle Pacific University

Follow this and additional works at: http://digitalcommons.spu.edu/honorsprojects

Part of the Condensed Matter Physics Commons

Recommended Citation

Cormode, Donley S., "Granular Convection and Crystallization of a Two-Dimensional Granular Medium" (2018). Honors Projects. 84.
http://digitalcommons.spu.edu/honorsprojects/84

This Honors Project is brought to you for free and open access by the University Scholars at Digital Commons @ SPU. It has been accepted for inclusion in Honors Projects by an authorized administrator of Digital Commons @ SPU.
Granular Convection and Crystallization of a Two-Dimensional Granular Medium

Donley S. Cormode

Faculty Advisor, Lane Seeley
Second Reader, John Lindberg

A project submitted in partial fulfillment of the requirements of the University Scholars Honors Program

Seattle Pacific University
2018

Approved __________________________
Date __________________________
Abstract

Granular media are everywhere from beaches to factories to your kitchen cabinets. There are a rich array of phenomena to study with granular media. These include granular convection, jamming, and crystallization. The systems tend to be macroscopic, so it is easy to collect data. The supplies are low-cost and easy to obtain. Studying granular media gives researchers the opportunity to explore foundational ideas in fields such as crystallography and condensed matter. This paper describes a simple, low cost apparatus used to study a vertically shaken two-dimensional granular medium of glass beads. This paper will also describe a few preliminary studies with this instrument. We examined the effect of the container’s geometry on the crystallization of the beads. We found evidence suggested that the beads transitioned from a random close pack arrangement to a hexagonal close pack. The paper ends with suggestions of further studies that could be done using this instrument.
1 Introduction

Granular media are everywhere. Sand, powders, even rice and coffee beans all fall into this category. Condensed matter physicists can use granular media to study many phenomena that appear elsewhere, including self-organization.[1] Granular solids sometimes flow like a fluid and sometimes jam or crystallize like a solid. One of the simplest granular media is a collection of uniform glass spheres or beads. Studying simple media like uniform glass beads allows researchers to gain a basic understanding of what happens in a granular system. Similarly, studying a system in two dimensions simplifies analysis which can then be generalized into higher dimensions. In this study, we built a simple system to study the convection and crystallization in a two-dimensional granular medium.

If you open a container of mixed nuts, it is likely that you will find the large Brazil nuts on top. This tendency for the largest particles to rise to the top of a shaken granular mixture is known as the Brazil nut effect. There are multiple theories for why this occurs. Different mechanisms dominate in different conditions. The two most significant mechanisms are convection and percolation.[2, 3, 4] Granular convection is when the particles in a shaken granular mixture move up the sides and down the middle of the container. This is similar to convection in a heating liquid on a stove. Percolation is when the smaller particles fall into voids below the intruder, thus pushing it upwards.[5] The Brazil nut effect is driven by both granular convection and percolation. Which one dominates depends on the conditions of the system. For the Brazil nut effect to occur in a vertically shaken system, the acceleration due to shaking must be greater than the acceleration due to gravity.[6] However, other conditions can prevent the Brazil nut effect from occurring even if the acceleration is large enough. The Brazil nut effect can be observed everywhere from mixing powders in the pharmaceutical industry to shifting inside cereal boxes. Understanding it better helps us both use it and prevent it.

In this study, attempts to observe the Brazil nut effect and granular convection were foiled by crystallization. The beads shifted from a random packing into a regular, repeating pattern. They then stopped moving. This meant there was neither convection nor percolation and therefore no Brazil nut effect. The rest of the study focused on observing this crystallization.

Atoms in a crystal are stacked in a regular, repeating pattern. In crystallography, atoms are modeled as hard spheres, like glass beads. Therefore, we use the language of crystals to discuss the crystalline arrangement of beads.[7, 8] Crystals are often defined by their basis and their lattice. The basis is the group of atoms that repeat to form the crystal. For the purpose of this study, all the crystals have a basis of one bead. If the system had two different types of beads (or atoms) or a more complicated crystal structure, then the basis would contain more beads. The crystal lattice describes the pattern that the basis follows. This study primarily discusses the hexagonal lattice. We describe a crystal using the crystal axes. The crystal axes connect points on a lattice. In two dimensions, the crystal axes define the parallelogram that is the building block of the crystal structure. In three dimensions, there are three axes that describe a parallelepiped. The parallelogram or parallelepiped defined by the crystal axes is the primitive unit cell. It is the basic building block of the
crystal. With the proper translations, repeating a unit cell can fill all space. The primitive unit cell is the unit cell with the smallest area (or volume). However, there are other unit cells that can also be helpful. For a two-dimensional crystal with a hexagonal lattice and a basis of one bead like ours, a useful unit cell is a regular hexagon that encloses approximately seven beads. See the white dashed hexagon in Figure 1b for an example. The crystal axes of a crystal also define the primitive translation vectors of that crystal. The crystal looks the same if translated by an integer multiple of the primitive translation vectors. In a two-dimensional hexagonal lattice, the crystal axes are of the same length and the angle between them is 120°.[7] Important features of a crystal can be described using its basis, lattice, axes, and unit cells.

There are many ways for beads to settle in a container. One useful way to study this is by studying the density of those beads. The density can be defined as the proportion of available space filled by hard spheres.[7] The maximum density is also known as the packing fraction and has been studied extensively for many lattices. In a two-dimensional system, the maximum density of particles arranged randomly has been experimentally determined to be 0.82.[9, 10] This is known as a random close pack (rcp). Lower densities produce an arrangement called random loose pack which will not be discussed further in this article. However, an ordered (or crystallized) system can become denser. Thue’s Theorem (named after the nineteenth century Norwegian mathematician) proves that the closest packing for
Figure 2: Three layers of hexagonal close pack and face centered cubic crystals in three dimensions. Both can be seen as stacked hexagonal lattices. For the hcp crystal, the layers follow a ABA pattern. For the fcc crystal, the layers follow a ABC pattern. The dotted line in the face centered cubic represents the location of the third layer (A) in the hexagonal close pack.

In three dimensions, the question of the closest packing of spheres is more complex. Johannes Kepler theorized that the closest packing for hard spheres in three dimensions produced a density of $\frac{\pi}{\sqrt{18}}$ or approximately 0.7405.\cite{7, 9} This is obtained with the hexagonal close pack lattice (hcp) or face centered cubic lattice (fcc). Both of these can be thought of hexagonal lattices stacked on top of each other and offset.\cite{7, 14} See Figure 2 for an illustration. Although Kepler first theorized this in the sixteenth century, it was not until the 1990s that the Kepler Conjecture was proved.\cite{13} Like in two-dimensions, the maximum rcp density has been determined experimentally. It is 0.64.\cite{11, 12, 13} Packing in three dimensions is more complex than in two dimensions.

Crystal imperfections are deviations from the ideal crystal structure. Because all of the beads in this study were of approximately the same size and shape and the crystals were in two dimensions, only three types of imperfections occurred.\cite{8} See Figure 3 for examples of these. The largest of these imperfections were grain boundaries. This happens when two crystalline regions meet. These regions have different orientations which creates a boundary. A smaller defect is a dislocation. A dislocation occurs when a plane (or line for a two-dimensional crystal) of atoms (or beads) ends in the middle of the crystal. This often causes...
a small change in the orientation of the crystal. The smallest defect is a point defect. In this system, the only point defect is a vacancy. This is an unoccupied site where an atom (or bead) would normally be in the crystal structure. These crystal defects help determine the properties of the actual crystal.

A common tool for analyzing granular media is statistical mechanics. The crystallization of shaken glass beads is analogous to the crystallization of atoms and molecules. The random close pack can be thought of as a liquid and the hexagonal close pack can be thought of as a solid.[12, 13] The system can be modeled using the methods of statistical mechanics. The crystallized system has a lower entropy. This can be seen by the increasing order in the system. However, crystallization will occur for a vertically shaken system. The increase in density allows more beads to sit lower. This decreases the gravitational potential energy (or conformational energy) of the system. This decrease offsets the decrease in entropy. The crystallization can be seen as a phase change and studied using the same methods.

Some previous work has been done. Scott and Kilgour measured the density of a three-dimensional rcp system of steel balls using similar methods.[12] However, they were specifically concerned with avoiding any order. They made a three dimensional system and focused on what was going on far from the edges. This study focused on a two-dimensional, vertically shaken system.

Understanding crystallization is important. The macroscopic system used here offers some insights to microscopic crystallization processes. In addition, understanding crystallization, close packing, and jamming (when the particles form a locked but disordered structure) of macroscopic systems helps researchers understand the movement of real granular materials, like sand and powders. Granular media also can be used to understand...
more complicated processes. It is difficult to observe crystallization on a microscopic scale. But studying granular media can help us understand crystallization on a macroscopic scale. Those results can be generalized to the microscopic. Studying crystallization in a granular medium can offer insight into the crystallization process.

Below, we describe that apparatus used to disturb the two-dimensional granular medium of glass beads. We then discuss some observations about crystallization, especially how it is effected by the geometry of the apparatus. We also look at the change in density of the system. We conclude with a discussion of further research that could be done with this apparatus.

2 Equipment and Methods

To study granular convection and crystallization, we built a container and filled it with glass beads. This container was shaken vertically and photographed using time lapse photography. The experimental setup is similar to others used to study the Brazil nut effect.[2, 16, 17] Scott and Kilgour also used a somewhat similar arrangement to study three dimensional random close packing.[12] The experimental setup in this research is inspired by previous researchers’ designs.

The container was made from acrylic, plastic, and balsa wood. The large sides were made of 0.125 inch thick acrylic. They are six inches wide and approximately six inches high. The walls were roughed by sandpaper to increase friction. The two walls were separated by two spacers made of 3/32 inch thick balsa wood. The acrylic and balsa walls were held together on the bottom by a plastic clamp. The sides are also held together by two screws. This
clamp also attaches the container to the wave generator. The container is light and can easily be altered.

Over the course of the study, it became clear that the shape of the container impacted crystallization. Therefore, we changed the shape of the sides and bottom of the container. Most of the initial research was done with a straight horizontal bottom and vertical sides. However, we then studied how crystallization changed when the sides or bottom of the container changed. One bottom had two isosceles triangles forming a saw-tooth surface. Another had two gentle curves following approximately the same path as the triangles in a sinusoidal pattern. The third unusual bottom has a 0.25 inch well in the center. See Figure 7. In addition to the straight sides, there were also saw-tooth and sinusoidal sides (Fig. 6). These followed the same pattern as the saw-tooth and sinusoidal bottoms. The container allowed easy changing of the sides and bottom.

The container was filled with glass beads. The beads are 2mm diameter borosilicate. Some beads were colored black. These were tracer particles.[18] If we wanted to track the movements of specific beads, we could watch the tracer particles. The container’s interior thickness is 3/32 inch or 2.38mm. This is wide enough that the beads move easily but maintains a single layer of beads. If the container’s interior width was 2.00mm, the minimum vertical distance between the centers of two adjacent beads would be 2.00mm. The extra 0.38mm means that the minimum distance between two adjacent beads is 1.96mm. The difference is 0.04mm or 40 microns, approximately the width of a human hair. The container was filled with 20.0g of beads in every run. The beads were poured in using a paper cone to encourage irregular dispersal. The system was then given one hard tap to disrupt any order that did form. Once filled, the container was then ready to be shaken.

The container was attached to a Pasco Scientific Mechanical Wave Driver. Two Wave Drivers were used over the course of the study to prevent either from becoming worn out. The two do not produce significantly different results after four minutes of shaking. The Wave Driver is attached to a function generator. The function generator creates a sinusoidal wave at 18.00 ± 0.02 Hz. This was the frequency with the greatest vertical displacement and the greatest response. The Mechanical Wave Driver shook the container.

Data was collected using a digital camera. Photographs of the container and beads were taken in five second intervals for four minutes. The first several pictures are before the shaking starts and the rest are during the shaking. This allowed us to compare the bead locations before shaking to the bead locations after shaking. It also allowed for the possibility of tracing individual beads’ movements throughout the time interval. In the following section, we will analyze the data from several container geometries.

3 Data

We tried to cause granular convection in order to observe the Brazil nut effect. In this research, the container had a straight bottom and sides. In addition to the beads, a round metal washer was placed at the bottom of the container (Figure 5). This was the intruder. A metal washer is commonly used as an intruder in experiments like this.[16] The Brazil nut
effect would have caused it to rise. The system was shaken at a variety of frequencies between 10 and 200 Hz for up to four hours. Time lapse photography showed the movement of the beads. The goal was to track the movement of specific the black tracer particles as they rose and fell. However, granular convection was never achieved. It is possible that the acceleration due to shaking never quite overcame the acceleration due to gravity. In addition, the system crystallized which prevented granular convection (Figure 5b). Therefore, the research focus shifted to studying the crystallization.

The initial container had both a flat horizontal bottom and flat vertical sides (Figure 6a). In this arrangement, the majority of the beads form a crystal where one crystal axis is parallel to the bottom. In all but one case, a region with a crystal axis parallel to the side formed along each side. These were typically narrow or nonexistent near the bottom and wider at the top. In one test, (which can be seen in Figure 9b) there was no crystallization parallel to the sides. The entire system was one crystal parallel to the flat bottom. This produced large gaps on the edges of the container where the crystal met the sides. All other container designs were compared to the container with a horizontal bottom and vertical sides.

Because it was clear that crystallization was affected by the shape of the container, we also looked at a few other shapes for the sides (Figure 6). Most of the beads formed a crystal
with an axis parallel to the flat bottom of the container. This is similar to what happened with the flat sides and flat bottom. However, some crystals formed along the sides of the saw-tooth pattern. They varied in size from only a few beads thick to much of the container. See the right side of Figure 6c for an example. The sinusoidal sides prevented as clear of a connection between the orientation of the sides and the orientation of the crystal. See Figure 6b for an example. Both the sinusoidal and saw-tooth designs created corners at the bottom of the container where some of the side was above the lowest beads. These bead movements were restricted while the container was shaking. The length of the container is large compared to the diameter of the beads. Therefore, the effect of the sides is negligible in the middle of the container. Changing the sides of the container affected the patterns of crystallization.

There were four designs for the bottom of the container tested. All four were tested with straight vertical sides. The flat bottom design was discussed above (Figure 6a). The other designs were a 0.25 inch well, a saw-tooth pattern, and a sinusoidal pattern (Figure 7). In all four patterns, some beads form crystals parallel to the straight sides. This region is widest near the top and gets narrower going down. It often does not reach the bottom of container. Crystallization occurred with all four designs.

The well was specifically designed to make crystallization more difficult. It is 35mm wide and 0.25 inches (or 6.35mm) deep. This prevents the 2mm diameter beads from filling it evenly. At the very bottom, on the sides of the well, crystals parallel to the bottom appear. The majority of the center, though, is taken up by a crystal with a different orientation. It does not appear to be parallel to the sides or the bottom. It is possible that a more precisely cut well would do more to prevent crystallization. The beads did not form a single large crystal in the middle the way they did in the flat bottomed container. The well changed the pattern of crystallization.

The sinusoidal bottom appears to do the most to frustrate crystallization (Figure 7b). At the bottom, the beads follow the curved pattern. This produces a section about four beads thick that forms a wave. They do not form a true crystal because the pattern is not repeating. Above that, more conventional crystals appear. They are extensions of the wave, so the crystal axes are not in any predictable direction. Despite the unpredictable
Figure 8: Grain boundaries and crystal domains in a crystalline system. The red lines highlight the most significant grain boundaries in each system. The red hexagons highlight the different orientations of the crystal axes and the lines off of the hexagons show one axis. Notice how the orientation of the crystal corresponds with nearby surfaces.

bottom, crystals still form. The sinusoidal bottom prevents the even crystallization of the flat bottomed container.

The saw-tooth bottom is more conducive to forming crystals (Figure 7c). Unlike the previous two designs, the beads can form crystals that align with the bottom. This leads to a series of crystals pointing in different directions. No one crystal orientation seems to dominate the structure. The orientation of the crystal axes seem to align with the saw-tooth pattern (see Figure 8b). The saw-tooth bottom creates a system with many different crystals, most of which are oriented along sides of the triangles.

In addition to identifying grain boundaries, we also looked at the change in density of the system. According to Thue’s Theorem, a perfectly crystallized system would have a packing fraction (or density) of 0.9068. The density was found by examining pictures of the system before and after the shaking. See Figure 9 for an example. Two one inch square boxes were drawn on the pictures. The density of beads inside the boxes was calculated. This was done by hand. Because this was a time-intensive process, this was only done for the system with flat sides and a flat bottom and the system with a saw-tooth bottom. The error in the density calculations is 0.05. For the entire container, there are approximately 109 beads per square inch before shaking and 123 beads per square inch after shaking. These densities do not describe the packing fraction, but they do give a sense of the transition. The density gives numbers to describe the transition from a liquid phase to a solid phase.

The density of the system for six different runs was calculated. Two runs had a saw-tooth bottom and the rest had a flat bottom and flat sides. For each system, two densities before shaking and two densities after shaking were found. Before shaking, the flat systems had densities between 0.72 and 0.75. After shaking, the densities were between 0.79 and 0.86. One system with a flat bottom and flat sides had densities of 0.83 and 0.86. This is within the error of 0.05 of perfect crystallization. For the saw-tooth systems, densities before shaking were between 0.71 and 0.76. After shaking, densities were between 0.74 and
Figure 9: An example of the system before and after shaking. The diagonal line shows the level of the beads before shaking. Notice how much the height has decreased due to shaking. Below each box is the density of beads inside that box.

0.79. This means that all runs were below the density limit for random close packing. The densities show an increase in density after shaking and some suggest higher densities than random close packing allows.

One weakness of this analysis is the large error. The maximum density for random close pack is only 0.087 less than the theoretical maximum for a hexagonal lattice. In this study, the density of the system always increased after shaking. However, some starting densities were higher than other ending densities. One problem was grain boundaries and other crystal flaws. By their very nature, these features decrease the density of the crystalline system. When a box encloses one of these flaws, the density goes down. Further analysis is needed to calculate the density more precisely.

This preliminary research showed some potential avenues of research using this instrument. We attempted to study the Brazil nut effect. We looked at crystallization, especially focusing on how the container geometry changes the pattern of crystallization. We also looked at the density of the particles before and after crystallizing.

4 Further Research and Conclusion

This instrument and data opens the doors for numerous follow-up studies. These potential avenues of research expand and continue the previous research. This includes research on granular convection, further density studies, changing the geometry of the container, and looking into jamming or three-dimensional systems. This instrument is a simple, low-cost way to study a granular medium.

The study started with granular convection. A follow-up study would first need to use an accelerometer to identify what acceleration the system is at now (and by how much it needs to increase). From there, the amplitude of the shaking would probably need to increase. One way to help with this would be attach springs to the top of the container. This would decrease the force on the mechanical wave driver. These adjustments might make it possible
for granular convection and the Brazil nut effect to occur.

Another follow-up study could examine the collected data using a computer algorithm. A computer program could identify the location of every bead in the container and track its movements through the time lapse. This study could also more accurately calculate the density of beads in the container. This would allow researchers to more accurately compare how different container configurations affect the packing of beads. This would greatly reduce the error on density. An algorithm may be able to identify different crystal domains. This would allow researchers to study how crystal defects like grain boundaries affect the density of the system. This follow up study would strengthen the tentative conclusions of this study.

Researchers could also explore how different container shapes impact crystallization. They could look at different shapes and the combination of different sides and bottoms. Researchers could also use 3D printing to obtain more precise shapes. One bottom in this study consisted of a well designed to frustrate crystallization. Printing could create more shapes like this with more exact dimensions. In a hexagonal lattice, the crystal planes are 60° apart. A bottom could be printed with equilateral triangles forming a saw-tooth pattern. This may promote crystallization differently than the flat bottom. Currently, the beads fill a space longer than it is tall. This means that the geometry of the sides does not affect the middle. Changing the length of the container would allow researchers to study these edge effects. A more detailed study on the effect of container geometries on crystallization can be done by 3D printing new geometries.

Future researchers could also change the beads. All of the research in this study was done with beads of the same material and diameter. The beads in this study could be mixed with beads of a slightly smaller diameter. A small number of these beads would simulate doping. This is a process done in the semiconductor industry where a small number of one type of atom (e.g. phosphorus) are added to a crystal of another type (e.g. silicon).[7] This changes the crystal structure slightly which changes the properties of the crystal. Researchers could also look at beads of the same diameter (2mm) but made of a different material such as steel or nylon. These beads would have different densities and coefficients of friction. Researchers could compare systems entirely made of each type of bead to see if the crystallization process is different. They could also look at a system with multiple types of beads. The different materials could produce all sorts of interesting results. Changing the beads introduces many additional research questions.

Other studies could also be done with more major changes to the experimental setup. A system to study jamming could be constructed. By making a new container (and possibly using two clamps), three dimensional motion could be studied. Both granular convection and crystallization occur in three dimensions. A study of container geometries or other factors could be performed. Further research on granular media is very possible.

This study looked at granular convection and crystallization in a vertically-shaken two-dimensional system. Although the research initially focused on granular convection, it shifted to looking at crystallization. Of six different possible container geometries, the one with flat sides and a flat bottom promoted crystallization the most. The density of certain regions of the system was also examined.
Acknowledgements

I would like to acknowledge the invaluable help that I received on this project. Lane Seeley walked with me through many frustrating months. John Lindberg offered feedback and encouragement. Jeff Norton assisted in building the granular convection container. Christine Chaney cheered me on. And my family supported me through moments of difficulty and moments of triumph.

References


[15] University of Cambridge, Dissemination of IT for the Promotion of Materials Science (DoITPoMS)


Appendix on Faith, Science, and Scholarship

The Jesuit priest Gerard Manley Hopkins wrote a poem that starts, “The world is charged with the grandeur of God.”[19] In this poem, he celebrates nature as God’s precious creation. As a physicist, I am trying to understand the patterns and rules of the natural world. Why does this crystal have certain electrical properties? What patterns emerge in shaken granular material and why? Why does a heated piece of iron glow? In this essay, I explore what it means for me to be both a Christian and physicist. My work as a physicist leads me to worship and wonder at God. I have chosen to study convection and crystallization in a granular medium because it allows me to explore a type of system that I havent worked with before, it contains a lot of interesting physics, and it is accessible experimentally. This project also gives me the opportunity to worship God through my work.

My background helps me integrate my life as a Christian and my work as a physicist. From a young age, I have known Christian scholars. My dad teaches leadership at Fuller Theological Seminary. One of my family’s closest friends is a well-known Christian philosopher. At my church growing up, I knew scholars in theology, chemistry, biology, math, and history. When I was in high school, a member of my church Dave Vosburg taught an adult Sunday school class on issues of faith and science. Dave is a professor of organic chemistry at a local college and regularly writes and speaks on this topic. This class exposed me to ideas about what it meant to be a scientist and a Christian. In his research, Dave sometimes synthesizes chemicals that have never been made before. In the class, Dave argued that God understands and knows about the chemicals he creates, even if they do not appear in nature. It is easy to see God in the natural world. But Dave talked about how he also sees God in these completely artificial chemicals. Dave’s way of seeing God in his research helps me see God in my own research. The Christian scholars in my life have given me a model for my own work.

Since coming to Seattle Pacific, I have continued to see models of faithful scholarship and to engage in conversations about faith and science. My professors have repeatedly demonstrated how to be faithful stewards of their gifts. I have taken several courses that have encouraged me to reflect on how my faith and scientific commitments overlap and compete. Before coming to Seattle Pacific, I did not understand the complexity of these discussions. As a Christian and a scientist, I will need to think critically about how my commitments interact. Faith and Science I encouraged me to think about how ideas about cosmology and the scientific method will interact with my faith. I saw how, despite the cultural message, my faith and my science did not need to be in conflict. I saw examples of faithful scientists like Nicolaus Copernicus, Johannes Kepler, and my professors. They did not seek to use science to confirm their faith or let their faith influence their science. Instead, both are ways of understanding the world in all its beauty. My time at SPU has helped me reflect on what it means for me to be a Christian and a scientist.

As a physicist, I study God’s creation. As Hopkins eloquently argues in his poem, all of creation sparks and shimmers with the grandeur of God. God is sovereign and whatever I study is God’s. I may be studying the physical properties of a man-made thin film or the movement of beads in a vertically-shaken system, but my work is still studying God’s world.
These things follow natural laws that belong to God. God is sovereign over these laws. When I study them, I am worshiping God. The wonder that I experience when looking at a crystal is wonder at God. Some might argue that focusing on the physical, natural world reduces God’s role in the world. As a physicist, I do practice methodological empiricism. I do not assume that the results of my studies are because God caused a miracle. However, that does not mean that God is not in the world I am studying. Close study of the natural world brings be closer to God because it is his world.

In his chapter in *Models for Christian Higher Education*, James D. Bratt examines the relationship between the Reformed tradition and education.[21] According to Bratt, the theological heritage of this tradition includes an emphasis on the glory of God and creation. Bratt argues that “joining comprehensiveness to transcendence in this way makes education a higher calling” (128). I do not disagree with this argument, but Bratt’s focus on higher education regardless of discipline misses the special importance of creation to the natural scientist. Bratt’s argument that creation is something transcendent means that the scientific focus on the world is good. To me, since the world is Gods glorious creation, studying it not only good, but the act of studying is worshipful. Patterns in granular media is a small glimpse of the order and beauty of creation. Science allows me to wonder at God’s creation and through that, God. Bratt’s argument captures some of my experience as a Christian scholar.

George M. Marsden discusses the Christians’ relationship with creation as well in *The Outrageous Idea of Christian Scholarship.*[20] Marsden argues that Christian scholars should employ what he calls “methodological secularism” (91). They should not expect a miracle to appear in their work. A miracle is by definition inexplicable. Crystallization is not driven by supernatural forces but by natural laws. When performing research, Christian scholars must look to physical explanations for natural phenomena, not spiritual ones. But that does not mean that they forget God’s presence in the world. Crystallization can point to God’s grandeur without losing its physical mechanisms. Marsden claims that this applies to all scholars, but especially to natural scientists. In this book, Marsden quotes the Hopkins poem that I quote above. He then argues that this awareness of God’s presence in the world “might not change one’s research methods or conclusions. . . but might have an impact. . . on one’s agenda in studying Gods creation in the first place” (92). My fellow physicists may study the natural world because it is interesting or because it is fun. I do too. But I also study the natural world because it is God’s creation. This added awareness encourages me to celebrate and wonder at the beauty and order in my findings. Marsden’s argument that the Christian view of creation can add to scholarship resonates with my view of scholarship.

Gerard Manley Hopkins celebrates God’s grandeur in his poetry. My work as a physicist allows me to study Gods creation. My research is an act of worship.