The Physics of Granular Materials

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For Mentorship this year, I worked with Dr. Behringer and Dan Howell at the Duke University Center for Nonlinear and Complex Systems. I began Mentorship with a purpose in mind--to explore an area of physics that was still a bit unfamiliar to me compared to other areas I've touched upon in high school. That area was nonlinear dynamics, and how it is applied to studying the physics of granular materials. To describe my research experience more fully, the first half of this paper will define granular materials and give some background on what my research was about. The second half of this paper will concentrate on my role in the lab, and importantly, what I learned as a result of my experiences there.

Background behind the physics of granular materials

The knowledge needed to learn more about granular materials comes from a larger field of physics called nonlinear dynamics. Nonlinear dynamics is the study of randomness within physical systems. An example of where nonlinear mathematics could be applied is a model of the direction a marble will fall if pushed off a balanced position on the head of a pin. Other examples are weather patterns, the formation of air currents in a room or water currents in a bathtub, turbulence, and especially, the random formation of piles of granular materials. The neat quality of nonlinear dynamics is that it tries to quantify both the amount of order and chaos in a chaotic system. It is very rare for a pile of a million particles to form in exactly the same way twice, but a pile always forms, and this is the order present in this system of chaos. Even more, there are certain patterns to the distribution of forces within a pile of particles, although two piles may never be exactly alike. The reason for studying nonlinear dynamics as it pertains to granular materials is to understand more clearly how complex, random processes such as erosion of beaches and mountain slopes occur, and also to understand how forces are distributed against the walls of a container holding granular material.

The definition of granular materials

Examples of granular materials are pharmaceuticals (pills), agricultural grains such as rice, wheat, popcorn kernels, and small seeds, and earth-formed objects such as gravel, pebbles, and sand. Granular materials are made up of distinct particles. They do not receive much energy of motion (kinetic energy) from increases in temperature as gas particles would; this is because the size of the particles are large enough to remain ungoverned by temperature changes. The particles in granular materials are large enough so that their motion can be described without having to use quantum physics, which accurately describes the motion of particles approaching atomic and subatomic size. Motion can be described using just regular, classical physics, which means that it is easy to predict the path of one particle when it is set into motion. A third characteristic of granular materials is that they collide inelastically, meaning that when multiple particles collide, the act of collision helps to dissipate the particles' kinetic energy, and as a result, the particles come to rest shortly after they collide with each other. This is assuming that the particles are roughly of the same mass and size. Finally, another characteristic of granular materials is that they are surrounded by a fluid or vacuum. The two most common media in which granular materials may be found are air and water.

Why granular materials research is important

The research I helped to carry out this year is very important because the physics of granular materials is largely undiscovered. Currently, lots of unnecessary money is being spent on the transport and containment of granular materials because we automatically assume that the material applies equal force to the walls of a container, say a silo. Because forces are distributed nonuniformly within the material, forces are also distributed nonuniformly against the walls of the silo. If the force is too great on some parts of the walls than on other parts, the silo may breach or collapse, thereby creating a huge mess that will take lots of time and money to clean up. To avoid such problems, we put more supports on the walls of the silo, which would be unnecessary if we knew how to design the silo to place the greatest support on just the areas that receive the most pressure from the material. Annually, billions of dollars are wasted on poor handling of granular materials. Besides helping to save money, there is also the need to learn more about granular materials physics because it may have unknown applications in other fields. When complex mathematics (mathematics involving “imaginary” numbers, versus the “real” numbers we are commonly used to dealing with) was developed, no one at the time knew that it could be used to describe electromagnetic waves such as radio waves and visible light in a simple manner. When granular materials physics becomes well developed, nobody knows what applications it may have.

My experiences in the lab

Dr. Behringer had two Science and Math students at his lab before. The last student was well-versed in Calculus 3, and had completed at least two years of physics before coming to lab. I was concurrently beginning my first year of calculus and my second year of physics. I probably should have had more math and physics experience, but I really wanted to have the experience of working in a real physics research laboratory. I felt I would have the ability to adapt what I have learned so far in math and physics to whatever situation would be placed before me in the lab, and I proved to be correct in my initial assumption.

For the beginning of the year, I helped to carry out a set of experiments involving the creation of three-dimensional piles. The piles were not made of sand, but of small, light plastic beads. The same mass of beads was added to a large funnel with a stopcock on the end so that the beads would not fall out prematurely. The mouth of the funnel was placed a certain distance over a large metal plate where the pile would later form. Located at the center of the metal plate was a pressure sensor. The pressure sensor was made of two plates across which the capacitance could be measured, and when particles fell down on the top plate, the distance between the two plates would decrease, and this would affect the capacitance of the sensor. The capacitance, therefore, was an indirect measurement of the force exerted by the pile at a certain distance from the center of the pile.

My task was to determine, at various distances away from the center of the base, the force on the base of a pile of constant mass. This was done by moving the mouth of the funnel away from the pressure sensor after seven force measurements had been taken at a particular distance from the center of the pile. Nine different distances were done, leading to sixty-three different trials that needed to be done. Once the funnel had been loaded with beads, the stopcock would be removed and the beads would be allowed to rain down onto the large metal plate below. As the height of the pile increased, the force on the pressure sensor would also increase. After all the particles had rained out, I then took a reading of the capacitance. This reading would later be converted to a force using an equation. Capacitance data was stored on a computer program which could model the change in capacitance over time. After collecting data, the funnel had to be reloaded, and the process was repeated.

Besides this particular experiment, I also read about various theories physicists and engineers had come up with to explain certain aspects of granular material motion. I received lots of papers which helped me to learn more about the research that had already been done on granular material motion. Not much research has been done in this area, and also, all of the theories that have been advanced do not apply to all situations. Therefore, there is not one theory yet that can fully explain the pressure distributions within granular materials.

Soon after winter break I began helping to design and build some of the experiments in the lab. One project I worked a lot on was the design of a new two-dimensional funnel (made of two plates of Plexiglas with a funnel-like hole cut out of a third piece sandwiched between the two plates). I had to make sure that the funnel area of the new funnel was the same as the old one, but the funnel had to be more compact than the first and several modifications had to be made so different experiments could be done with this new funnel. I also helped to build supporting frames for other experimental devices, and learned how to use shop equipment by doing so. New things that I learned to do were to cut wood with an electric saw and to drill holes in metal. The last half of the year was particularly nice because I was able to see how all the theory I had learned through papers and talks in the first half of the year could be applied to actual experiments. Being able to help build the experiments also helped me to achieve a greater understanding of the research process in physics.

My mentors proved to be highly knowledgeable in their areas of research, and enjoyed sharing their knowledge with me. They have been both helpful and enthusiastic, and have proven to be inexhaustible sources of answers for all my questions. To help me learn more about nonlinear dynamics and how physics research in general is conducted, Dan was very active in finding me things to work on in the lab. As a result of these tasks I was given, I have learned how to measure and partially analyze force distributions underneath the base of a pile of granular material. Dan also gave me the opportunity to sit in on nonlinear dynamics lectures. Also, Dr. Behringer found lots of papers written by major contributors to granular materials physics for me to read so that I could learn more about this area of research.

One of my most valuable experiences came after I had finished reading a paper on how to analyze stress within granular materials. Within the paper were several differential equations of a complexity I had not yet encountered in calculus, and probably would not have encountered until my third year in college. So that I could understand the paper more effectively, Dan showed me how those equations were derived, and how to solve them. It was very easy to follow his explanations of what the equations meant, and how they related to what I had learned so far about stress in granular materials. By understanding these connections, I became more aware of how calculus is not abstract, but very real in that it actually describes real situations.

What I learned as a result of my Mentorship

When I first heard of an opening at Duke in nonlinear dynamics, I told myself, "I have to be there." I wanted to know how scientists dealt with the randomness of motion often encountered in physics. In high school, students generally do not know enough math to do anything more than physics problems with a high degree of symmetry or uniformity. However, there *is* chaos in real physical situations, and by working in the lab, I learned that there *are* ways to deal with unpredictable motion in granular materials. Two of the most important things I have learned from nonlinear dynamics being applied in granular materials research are:

- Forces are distributed in stress chains in granular materials, whereas for liquids and solids, there is a uniform distribution.

- Although no two piles under the same conditions of formation may ever be identical, there is still a certain degree of order within the piles that equations may eventually be able to describe.

What I would recommend to others about Mentorship

It is important to learn more about one's fields of interest because what a person thinks he or she might want to do after college may not be what he or she actually ends up doing. Perhaps the person is very strong or not too strong in a particular area of knowledge or skill required to be active in a certain field, and it is important to find this out before that person gets out into the world of work. Mentorship gave me the opportunity to make these kinds of self-discoveries. I really enjoyed my Mentorship experience this year, both because I got a chance to see what life is like within a physics research laboratory and because I learned new ways to apply old skills.

Before I came to Dr. Behringer's lab, I knew I wanted to do physics research but I was not yet sure of what type of research I wanted to do. Working in the lab allowed me to see what granular materials research was like, and through talks with professors and graduate students, I also learned more about other research areas in nonlinear dynamics. I also got a chance to survey the major areas of physics research represented at Duke, such as low-temperature, condensed matter, and high-energy physics. By seeing how research is conducted in a physics laboratory and by getting to meet people doing research in different areas of physics, I have narrowed down my fields of interest.

My strong point in physics has always been synthesizing some idea from seemingly unrelated bits of information, or trying to find a pattern where none currently exists. Although I learned a lot about granular materials research, I discovered that my best abilities might be in pursuing research in theoretical nuclear/particle physics, where researchers are currently trying to discover the fundamental structure, composition, and evolution of the universe. Now that I have learned a whole year of calculus, I feel confident in my mathematical abilities, and I think that taking on the mathematics required for theoretical physics might not be too difficult. Of particular interests to me are nuclear fusion, gravity, and developing experiments to test string theory. If I had not worked at my lab this year, I might not have decided I had the ability to tackle the areas of physics research I have interests in, and I owe this personal discovery to being in the Mentorship Program.

The only regrettable part of my experience this year that I can think of was that I could not learn all the nonlinear dynamics I needed to know so I could contribute more to the research going on in the lab. I did, however, learn a lot just by being able to participate there. Besides that, I would not change a thing about my Mentorship experience. Working at my lab was a way of getting in on the ground floor of my future, and I am very grateful that I received the opportunity to work there.

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