How to do research  (Well at least a few hints!)

Knowing that most of you have not really been responsible for doing any research, I will try to take some of the mystery out of doing experiments. The basic idea is to find something interesting and by doing experiments discover what you can about that system or phenomenon. Then you must reduce the results of tons of work down into some simple form that can be communicated very clearly to others in the physics community. In other words, you must write a good clear paper, or your work will be ignored!

In modern research, one often tries to discover if the data are consistent with an existing theory. If no theory exists, or if none of the existing ones is consistent with the data, you often try very hard to discover an equation or set of equations that is consistent with your data. This enables others to have easy access to your findings in a way that will guide the development of any new theories. Thus, experiment plays two crucial roles in modern physics. First, most truly new phenomena, such as high temperature superconductivity, are discovered by experiment. Second, there are usually a number of competing theories in any area, and often only experiment can decide between them.

In testing theories by experiment, it is important to keep the following in mind. Experiment can never prove that a theory is correct, because almost any theory predicts an infinite number of results, not all of which can possibly be tested. Instead, any theory of interest can be tested against experiment by asking if the theory is consistent with the data. Note that I did not say agrees with the data, I said is consistent with the data. No theory will agree exactly with your data, so you must answer the following question. “Does the theory differ from my data by so much that I am willing to bet my reputation by stating in print that the theory is incorrect?” If so, it is inconsistent with your data. Once a theory is found to be inconsistent with the results of careful experimentation, it is soon discarded and replaced by an improved theory that is consistent. This process goes on constantly in modern physics. Theorists are usually delighted when you expose the shortcomings of current theoretical understanding, because it means there is some interesting new theoretical development to be undertaken.

OK, enough of these generalities, what should I do in this class? You will soon realize that several factors may be relevant in any given experiment. As beginners, you will find it very difficult to avoid fixing all but one factor at arbitrary values and carefully measuring something while changing only one variable. You will take increasingly precise data in this way, and when I ask you how important the other variable are, i.e. how much they affect what you are measuring, you will have no idea. Don't proceed in this way. Instead, do a series of rough experiments before you take any serious data, to find out what matters and how much it matters. Once you have a reasonable feel for all the variables, you can plan an intelligent systematic investigation and carry it out. You should come to your first consultation with a clear idea of what you are
planning to measure based on what you have already learned by this sort of rough experimentation.

Another thing to keep in mind when you are planning your experiments and when writing your paper is that you must essentially construct a mathematical proof that what you conclude is true really follows from your data and/or from accepted laws of physics. If you take a great deal of very precise data, and then overlook some logical inconsistency in the process whereby you reach conclusions based on the data, the final result is not likely to be very valuable. You should always imagine some horribly smart person, who does not believe a word you say, is the reviewer who will decide if your conclusions are correct. Don’t leave this fellow any way to escape from accepting your conclusions. Don’t leave any doubt about the data, and don’t leave any weakness in the analysis. If you cannot eliminate some possible problem with the data or the analysis, do not ignore it. Instead, state what the problem is and what could possibly be done about it in the future. If you ignore it, someone else will soon point out, in print or at a meeting, that you never considered the problem.

How can you tell if your data are consistent with a theory or with an equation you have dreamed up yourself? The most common way to do this is what is called “least-mean-square fitting” the theory to the data. This means varying all the unknown parameters in the theory until the theory agrees with the data as well as possible. For example, suppose you want to know whether the theory that the period of a pendulum varies as the square of the pendulum’s length is consistent with your data. The theory can be written as \( T(L) = A\sqrt{L} \), where \( T \) is the theoretical period, \( L \) is the length of the pendulum and \( A \) is an adjustable parameter. You can use a computer to adjust \( A \) until you have minimized the deviation between the theory and your data. If the resulting function passes so close to your data that you can’t say it is wrong, then the theory is OK! You will be able to do this using a program called Mathematica, which is installed on each of the computers in the lab. You will also be able to use Mathematica to make nice publication quality plots of your data for your final papers. It is OK to use any old graphs in discussing your work with me, provided they are clear, but the final paper must use publication quality graphs made using Mathematica. My advice is to think about the figures you want to have in your paper, and start producing the final figures as soon as possible, and definitely finish the figures before you do much writing.