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How Do You Mass What You Cannot See? Using Paper Clips to Help Students Learn How Electron Mass Was First Measured

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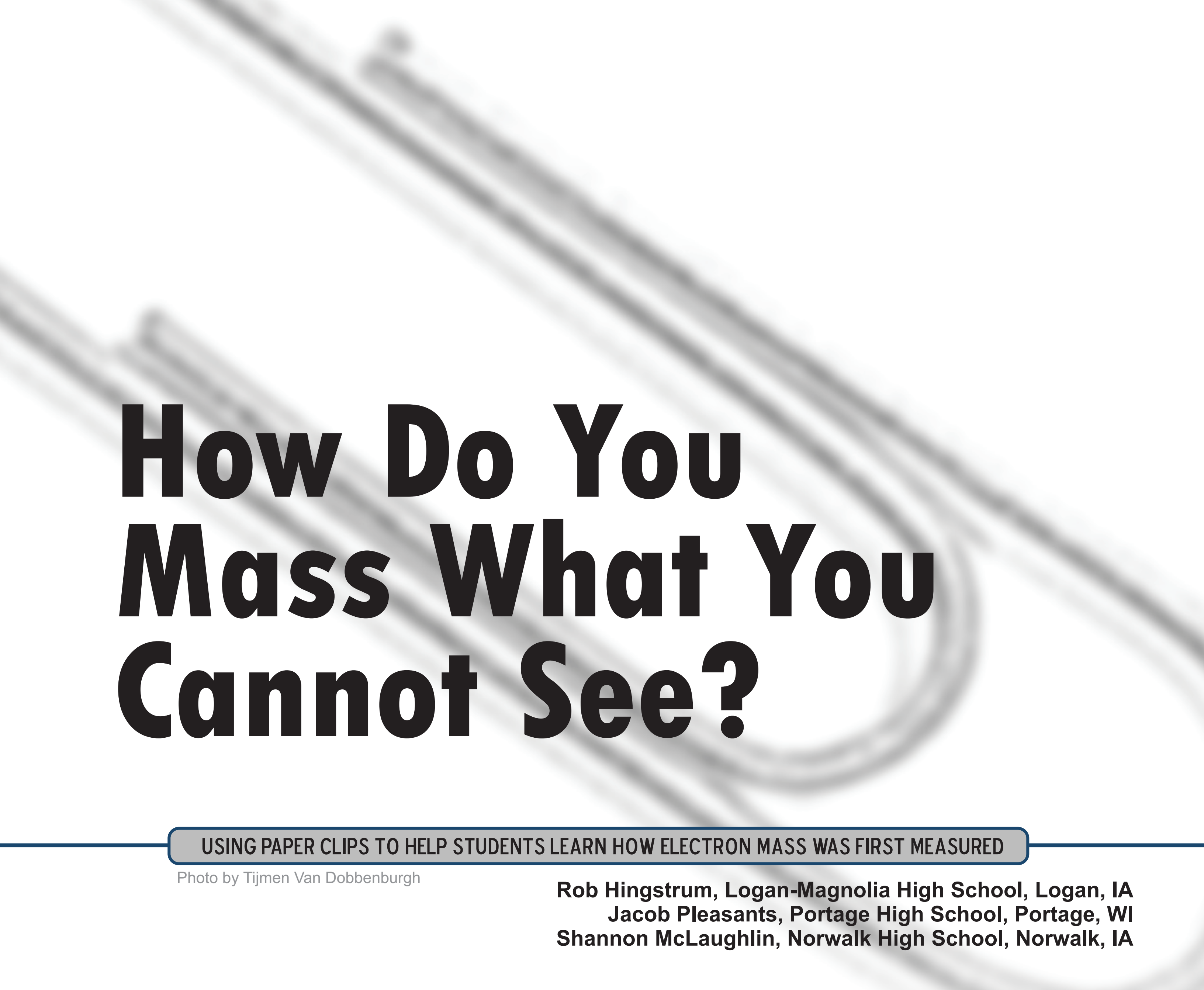

How Do You Mass What You Cannot See?

USING PAPER CLIPS TO HELP STUDENTS LEARN HOW ELECTRON MASS WAS FIRST MEASURED

Photo by Tijmen Van Dobbenburgh

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ABSTRACT: Many students wrongly presume that scientific knowledge is mysteriously discovered and often believe the development of this knowledge is beyond their ability to comprehend. The activity presented here – appropriate for high-school chemistry and physics students – challenges these misconceptions. Students are engaged in thinking and creativity similar to how the first scientists accurately measured the mass and charge of an electron. Through this process, students develop a deep understanding of how the mass and charge of an individual electron was determined. *This activity addresses National Science Education Standards A, B, E, and G and Iowa teaching Standards 1, 2, 3, 4,5, and 6.*

Science ideas are too often presented without addressing how they were developed and came to be accepted. For instance, in chemistry and physics courses, fundamental quantitative units such as the mass and charge of subatomic particles are often provided without engaging students in understanding *how* those quantities were determined. How could scientists ever have determined the mass of something as tiny as an electron? In general, how do scientists know what they know about the natural world?

The activity described here demystifies the process by which scientists determined the mass and charge of an electron. This activity originally appeared in CRISTAL program (University of Northern Iowa, n.d.), but what is presented here has been modified to further promote creativity, critical thinking, deep understanding of science content, understanding of the nature of science, and make more clear the crucial role of the teacher during the activity. This activity requires students to engage in the sort of investigative problem solving that is characteristic of the work of scientists. As such, we do not provide students a prefabricated procedure. With the teacher's guidance, students develop and carry out their own investigations. This task is difficult for students, and the success of the activity is dependent on students' prior understanding of several important science ideas and the way the teacher interacts with students. Before embarking upon this activity, students must understand the particulate nature of matter. More specifically, students must understand that atoms cannot be seen and that they, in turn, consist of even more fundamental particles. Students must also understand how an object's mass is related to the number of particles comprising the object.

Beginning the investigation

To begin the activity, we show students several containers full of paper clips and inform them their task is to determine the mass of a single paper clip (for materials, see Figure 1). However, we also indicate that the paper clips will serve as a model for particles of a substance, such as lead. We ask students the following questions to help them understand the new challenges that this model presents:

- If you tried to simply pick up and mass a single atom of lead or any other element, what problems might you encounter?
- Given that we cannot actually see atoms, how would we know if we only had a single atom?

FIGURE 1

Materials needed for the activity.

- Paper clips (50-100 for every two students)
- Containers for paper clips
- Analytic scales/balances

Because we are treating the paper clips as a model of something we cannot see, we introduce the following restriction in this activity: under no circumstance may students count any paper clips. Throughout the lab, the teacher must carefully monitor students so that this restriction is followed. We ask the following question to ensure students understand what the paper clips are modeling.

- Why is this restriction necessary for understanding how scientists had to approach the problem of investigating atoms and subatomic particles?
- Given this restriction, why will you not be able to directly mass a single paper clip?

Before distributing paper clips, we have the students in groups of two develop a list of measurements that would help them find the mass of a single paper clip. As we walk around observing and listening to students, for each idea they propose, we ask how they would actually use that measurement in a meaningful way. As an example, students often want to determine the density of paper clips. We try to guide students toward understanding that this particular measurement will not be of much benefit to them. Specifically, we ask,

- How does the density of one paper clip compare to the density of 100 paper clips? or
- Considering the amount of material does not affect density, why might finding the density be of little use?

After approximately five minutes, we then ask for students' ideas and place them on the board. The use of wait-time I and II and positive voice-intonation and non-verbal behaviors (e.g. inquisitive look, raised eyebrows, smiling, leaning forward, etc) are crucial during this discussion. Wait-time I and II encourages greater critical analysis of ideas and generally improves the quality of class discussion (Rowe, 1986). By using positive non-verbals along with wait-time I and II, students will see we are truly interested in their ideas and will more likely offer them (Clough, Berg & Olson, 2009).

Students often need help coming up with the idea that more particles, or paper clips, corresponds with more mass. To do this we pass around a set of standardized masses and ask

- Assuming the masses are all made of the same material, what is the cause of the difference in mass between them?

We then have the students discuss what mass measurements they might make that would result in meaningful information about the number of paper clips. While the students are discussing this, we nonchalantly walk around sloshing paper clips between two containers in order to plant the idea of measuring the mass of various quantities of paper clips. However, student will not likely understand how these measurements will be useful. To spark students' attention to patterns that exist among different quantities of massed paperclips, we wait an appropriate amount of time while students wrestle with the task before posing questions such as:

- Suppose we took many mass measurements for different quantities of paper clips. What patterns do you predict we might be able to infer?
- Given how many groups of students we have, how many different trials should each group conduct in order for us to have enough data to determine what pattern, if any, might account for our data?

We task the students with collecting as much data as they deem necessary. After the students collect their data, we have them share their data to produce a class set.

Interpreting the Data

The data analysis phase of this activity is challenging for students, and they will likely require significant guidance. However, guidance does not mean telling students how to analyze their data. Simply telling students how to make sense of their data would undermine the mental engagement that is crucial for deeply understanding the data analysis and science concept we have targeted. Thus, students must still maintain control of decision-making in this phase of the activity. So instead of telling students how to analyze the data, we ask:

- What patterns, if any, can you infer from this set of data?
- What sorts of things could you do with this data in order to be more certain whether a pattern can be inferred?

The language of these questions has been carefully chosen to reflect the important nature of science idea that datum does not speak for itself. Throughout the activity, we take care in avoiding words and phrases such as "what do these data tell you?" While using consistent language is important, these ideas must also be explicitly discussed in order for learning to take place (Clough, 1995). Whether this discussion occurs at this point in the activity or later on must be decided by the teacher. We choose to draw students' attention here to how scientists must make sense of data, and how this demands imagination and creativity, by asking questions such as:

- I have been careful to ask you what patterns, if any, can you *infer* from these sets of data. How is that different than asking you what the data tell you?
- Many people wrongly think that science places little value on creativity. Given that scientists must make sense of data, what crucial role does creativity and imagination play in doing science?

At this point, students may wish to collect more data. Students may also suggest that the data be organized or graphed in some way. When students suggest these ideas, we encourage them to do so, but also ask them to describe in what ways their suggestions will be useful. We first want to guide students to organize their data in a table from low to high by asking how they can organize the numbers before graphing the data. Once arranged in this way, students have in the past suggested that a new data table be made of the differences between each consecutive entry in the first table. If students want to graph their data, they usually want to make a line graph. When students raise this idea, they struggle to identify what two variables they will graph so we ask,

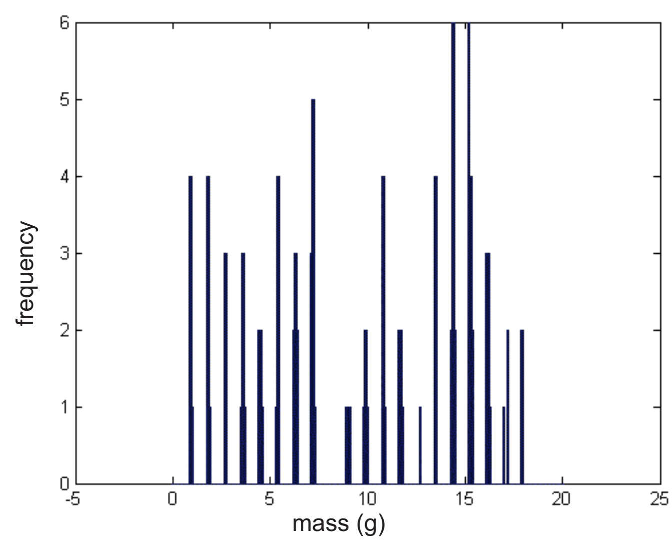
- How might knowing the frequency of different masses be useful?

We use this opportunity to introduce students to a histogram (Figure 1). While a histogram is a useful data analysis tool, it is not needed to complete the activity.

We again ask students what patterns they can infer from their data, and provided students have collected enough data, they identify that their mass measurements appear to clump around certain values. That is, students may have several values around 36.0 g and several values around 37.0 g, but no measurements in between. Some of the questions we ask students to stimulate this discussion are:

- Which values, if any, seem to be represented more than others in your data?
- How might you explain why a group measured the same mass on two different trials?
- What is the smallest difference between any two mass measurements? What might account for that particular pattern?
- We have several mass measurements around ___ grams and several around ___ grams, but none in between. By how many paper clips do you think those two sets of measurements differ?

FIGURE 2
Sample Histogram (see enlarged version on last page)



The questions we ask and the ensuing discussion serve to eventually develop the idea that no two mass measurements can differ in mass by less than the mass of a single paper clip. We write this idea on the board to make it as explicit as possible, and we then discuss how it can be used to determine the mass of a single paper clip.

Links to the Nature of Science

This activity provides numerous opportunities for connections to the history and nature of science (NOS), which is an important goal for science education (AAAS, 1989; NRC,1996; NSTA, 2000). Students who accurately understand the NOS have more positive attitudes toward science and more deeply understand many science concepts (Clough, 2004). For instance, the way we address the NOS in this activity helps students deeply understand how scientists, using creativity and ingenuity, may address seemingly insolvable problems and come to the conclusions that we now teach in science courses. Thus, students come to better understand what science is, how scientists solve problems, and what makes science an interesting and rewarding pursuit. Not surprisingly, students are more engaged and better understand the science content.

We will briefly describe a few of the NOS connections that we find are promoted particularly well by this activity, although other ideas can also be addressed. We place these pieces at the end of the activity, but NOS connections are often best made during the activity, as illustrated earlier.

We discuss with students which assumptions are embedded in their laboratory procedure and their interpretation of data: namely, that all paper clips have the same mass. We ask students to consider how difficult this activity would be if this assumption were not the case. More importantly, we ask students to identify some ways in which this assumption was validated through the activity. If all paper clips were not of the same mass, students would have been completely unable to infer any pattern in their data. Because they were able to infer a pattern, the assumption gains validity, although it is still not a certainty.

We then explain to students how scientists must frequently make assumptions when carrying out investigations in order to make any progress at all. These assumptions do not diminish the utility of the scientific work because they, like any scientific idea, can be tested against the natural world. We ask students to discuss how assumptions contribute to the objective and subjective nature of science. Thus, students grow in their understanding regarding the crucial role assumptions play in science, the growing confidence in those assumptions with supporting data while remembering that all scientific knowledge is open to reexamination.

We also discuss with students how they used creativity to solve the problem at hand. We also make clear to students that scientists must be creative in their work as well. We use the example of Robert Millikan, whose work was very similar to what students did in their activity. Without creativity, Millikan would not have designed the ingenious experiment for which he earned a Nobel Prize.

Links to Science Content

The primary goal of this activity is to help students understand how scientists know such mysterious quantities as the mass and charge of the electron. Throughout this activity, we use paper clips as a model for particles on the atomic scale. After concluding the investigation, we discuss with students the limitations of their procedure. We ask students to consider what problems they would encounter if they tried to apply their laboratory procedure to the task of determining the mass of a single grain of sand. Even if all sand grains had the same mass, the lack of precision in the measuring device (the scale) would foil the procedure. This limitation is only magnified on the atomic scale.

However, we now indicate to students that although precision in mass measurements is quite difficult, many procedures exist that allow for quite accurate measures of electric charge. We make clear that, through some complex equipment, the electric charge of a single electron could be detected. In this way, the problem that the students investigated is analogous to the problem of determining the charge of a single electron. We discuss with students how Robert Millikan had the insight to use this procedure and became the first experimental scientist to accurately determine the charge of a single electron.

From here, we discuss with students how scientists used the knowledge of the electron's charge to determine its mass. In addition, we might discuss with students how this information was used to determine Avogadro's Number. Through all of this, the important point to make is that determining these fundamental quantities is no trivial matter. Scientists cannot simply put an electron on a balance and determine its mass. Rather, scientists must use creative means to measure such quantities indirectly. This is a recurring theme in science which also applies to such quantities as the masses of the Earth, Sun, and Moon. By helping students understand how this information came to be known, we demystify both the natural world and the nature of science.

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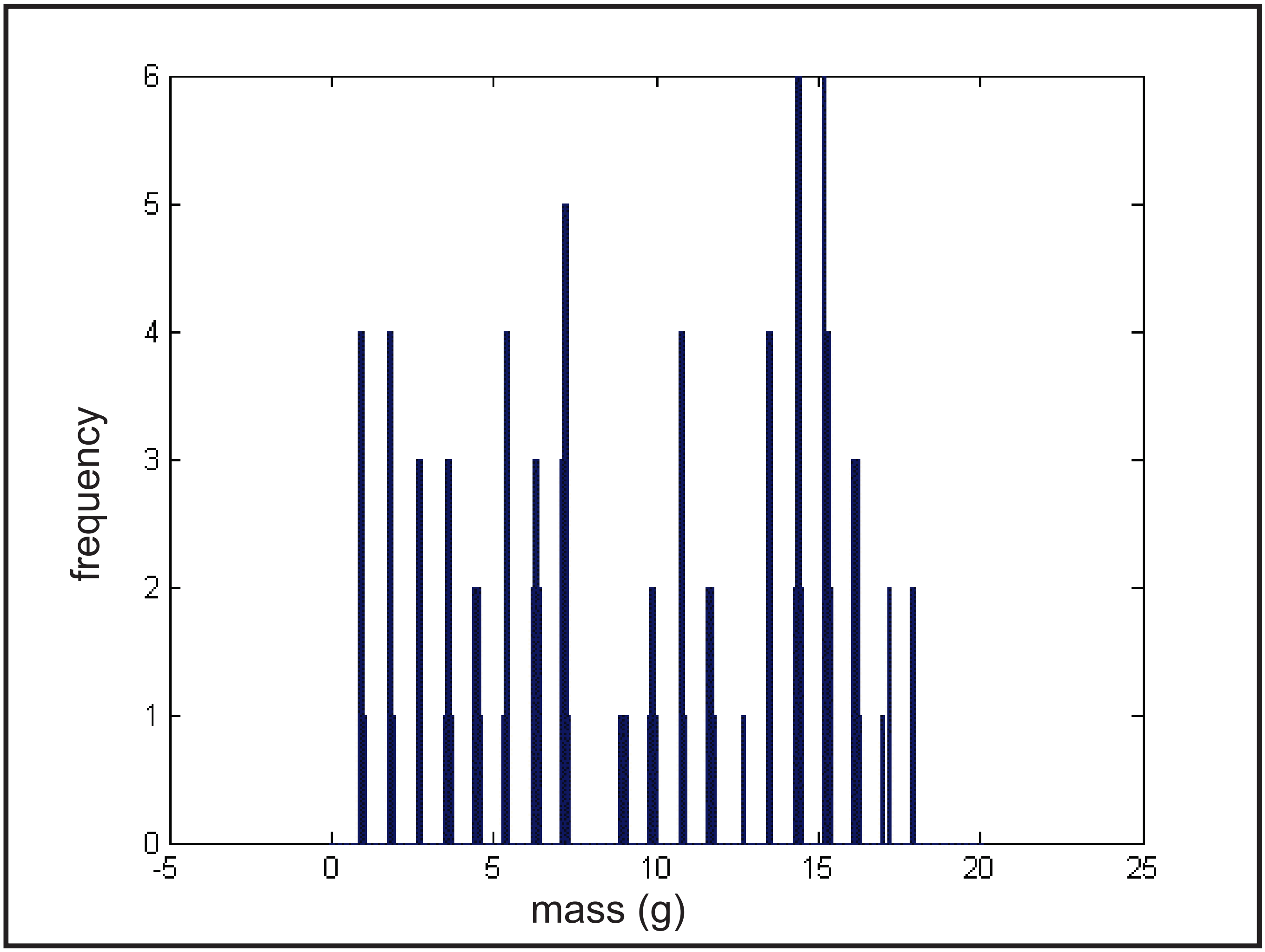

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