Iowa Science Teachers Journal

Volume 33 | Number 2 Article 6

2006

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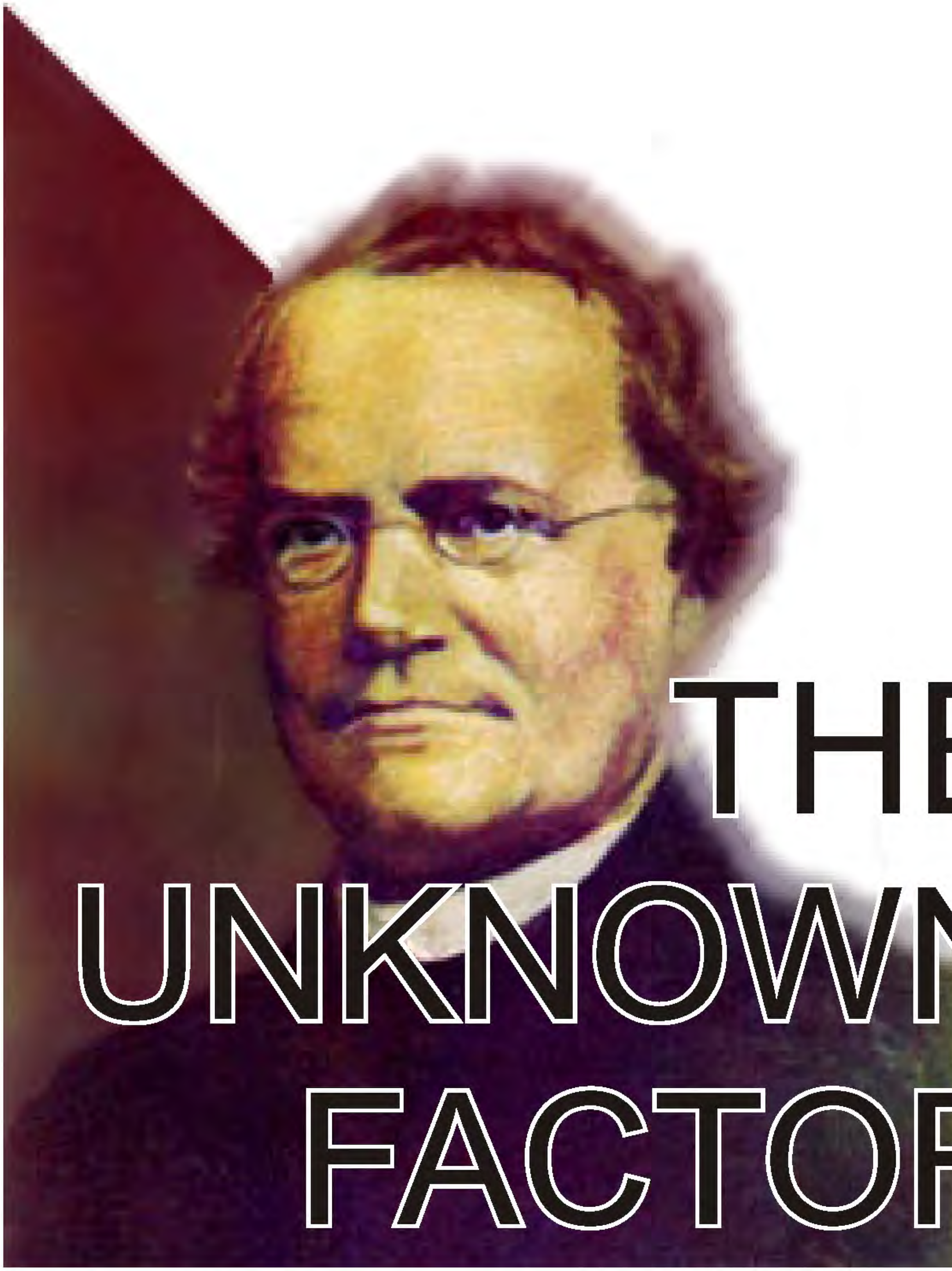

THE UNKNOWN FACTOR

Helping Students Understand Mendelian Genetics and the Nature of Science

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ABSTRACT: Teaching science concepts in the same chronological order that the knowledge was developed by the scientific community is an effective way of promoting understanding of the concept as well as a greater appreciation for scientific inquiry. This activity mentally engages students and provides them a sense of discovery that Gregor Mendel must have felt over 150 years ago when he came to understand inheritance. Finally, by putting Mendelian genetics into a historical perspective, students will gain a greater understanding of scientific processes and the history and nature of science. *This activity promotes National Science Education Content Standards A, C, E and G and Iowa Teaching Standards 2, 3, and 5.*

Introduction

Activities, articles, historical stories, and discussions that explicitly draw students' attention to what science is and how it works have been shown to promote students' understanding of the nature of science (Abd-El-Khalick & Lederman, 2000; Clough et al., 2006; Cossman 1969, Crumb, 1965; Klopfer and Cooley, 1963). Moreover, teaching science concepts in a sequence that reflects their historical development can help students better understand those ideas and their significance (Matthews, 1994). After all, early scientists made sense of phenomena in light of what they already knew, and that also reflects how students learn.

Because science teachers possess a great deal of knowledge that students do not, they may easily sequence instruction in a way that makes sense to them, but not to novices learning the science concepts for the first time. For instance, cell division, chromosomes, mitosis, and even DNA often precede instruction regarding Mendelian genetics. A common rationale for this sequencing is that Mendel's laws of heredity are best understood in terms of those prior concepts. But that rationale does not take into account the ideas about heredity that students bring to instruction. Moreover, it distorts the history and nature of science, and interferes in students' understanding of the significance of Mendel's work.

For these reasons, I begin instruction regarding heredity with what puzzled Mendel and his contemporaries at that time. Beginning at that point better integrates students' prior knowledge, and it creates an opportunity for me to have students experience a sense of scientific inquiry, inventiveness and discovery that Mendel experienced over 150 years ago. In doing so, students better understand Mendel's principles, how he came to them, and aspects of the nature of science.

Historical Ideas Regarding Heredity

Prior to this activity, my students have explored mechanisms of reproduction in flowering plants, so they have knowledge of plant breeding similar to what Gregor Mendel possessed. To begin this unit, I introduce my students to some of the following ideas regarding inheritance that existed prior to Mendel's contributions.

Greeks: Males and females contribute a fluid. Each part of the body contributes a fluid (eye fluid, finger fluid etc). At conception, the fluids compete. Gender is also determined by this competition of fluids.

Middle Ages: Acceptance of spontaneous generation (i.e. that living organisms could arise from non-living substances). For example, flies could spontaneously generate from meat, and fleas could spontaneously generate from mud and dirt.

Francesco Redi: Put meat in jars (some covered, some not covered) to disprove spontaneous generation.

Anton Van Leeuwenhoek: Created the first microscope. Using this he observed fleas mating and sperm. Some speculate that all organisms are sexual and that sperm might have a preformed individual developed *in utero*.

William Harvey: believed females had eggs by analogy because chickens had eggs. Finally found a mammal egg (dog) in 1827.

When addressing these ideas, drawing students to key ideas regarding the nature of science is important. For instance, at the appropriate time in the heredity unit, use the eventual abandonment of the idea that a preformed individual existed inside of a sperm cell to illustrate how accepted ideas may change in light of new evidence. Furthermore, how technological advances may aid science should be highlighted in Anton Van Leeuwenhoek's creation of a microscope and how it helped advance thinking in heredity.

Introducing Monohybrid crosses

Begin by introducing your students to Gregor Mendel, an Austrian monk who worked in a monastery garden and performed experiments on pea plants. Tell students that Mendel worked with peas that had different traits like yellow peas, green peas, purple flowers, white flowers, peas that were wrinkled and smooth. At some point he decided to focus on one trait and cross-pollinate peas with different traits. For example, he decided to cross pea plants that produced different colored peas. Specifically, he crossed the flowers of pea plants that produced yellow peas and plants that produced green peas. Ask students questions like, "What do you think the progeny of a cross between a yellow and a green pea would look like?" Also ask students what they think Mendel would have expected from this cross prior to performing it.

Asking for predictions is crucial for mentally engaging students, for gaining an understanding of their preconceptions regarding inheritance, and for helping them consider what Mendel was attempting to understand.

Often times, students will express ideas indicating they have had prior instruction regarding Mendelian genetics, but then fail to correctly predict the outcome of crosses. Some common student responses include:

- The resulting peas will be a yellowish green
- The resulting peas will be either yellow or green
- The peas will fail to reproduce because they are incompatible.

I often ask students to record their predictions and explanations in their notebook. While students write, I walk around observing their predictions and their speculations regarding Mendel's thinking, and I make a mental note of what they write and use it in the ensuing discussion.

I begin the discussion by asking, "What might someone who had never observed this cross predict the outcome to be?" Use wait-time and positive non-verbal behaviors to draw out all different responses you noted when observing students' writing. Then ask, "What reasonable rationale could be given in defense of each speculated result?" The phrasing of these questions and acknowledging all proposed answers is important to create a safe intellectual environment that emphasizes reasoning and understanding.

After this discussion, students WANT to know the results that Mendel observed. Tell students that Mendel's cross resulted in plants that later produced only yellow peas. Ask students to again provide an explanation for this result and record their explanations in their notebooks. More often than not, students will claim that the yellow color is more powerful or dominant than the green color. Tell them that Mendel came up with the same explanation and referred to the yellow trait as dominant and the green trait as recessive. The approach described above mentally engages students and introduces the more formal science concepts of dominance and recessive *after* students have some experience with the concept.

Continuing with the historical study, tell students that Mendel then decided to plant all of these yellow peas, raise them to adulthood and cross-pollinate all of the resultant yellow peas with themselves. Now use the same approach as above. Ask students, "What do you expect from this cross?" Follow this with, "What do you think Mendel would have expected from this cross prior to performing it. Have students explain their reasoning for both predictions. Most students will predict that all of the peas will be yellow because yellow is the dominant color. Very rarely will students predict any green peas resulting from the cross of two yellow pea plants.

After discussing their explanations, I tell students that I contacted a museum (any well known museum works fine, but I usually say the Smithsonian) and requested the peas that resulted from this cross that Mendel performed. At this point, I direct students into a lab, give groups of two a sample of the peas and tell them to count the peas and provide an explanation for Mendel's results and record their count/explanation in their notebook. I also tell them not to lose any of the priceless Mendel peas that we have on loan from the museum! Students immediately note that most of the peas are yellow (just by observing them) but are puzzled that a significant number of peas are green (Figure 1). Providing an explanation that accounts for this is challenging to students, yet critical for their understanding of Mendelian genetics. Most students hesitantly, almost shyly, put forth the possibility that at least some of whatever causes the green trait must be left in the yellow peas. Some pose this as a question, "Could some of whatever is causing the green be left in the yellow peas, but hidden?" This is the time to ask, "How does proposing that idea help us account for the data?" This is important to help students understand that data doesn't tell the investigator what is the correct explanation. Instead, scientists must invent ideas that will account for the data.

FIGURE 1

Pea samples are observed, sorted and explained by students.

This is an appropriate time to introduce the concepts phenotype and genotype. Furthermore, I usually begin to define the color unit as a "factor" as this is the term that Mendel used to explain inheritance. At a more appropriate time, we will begin to refer to these "factors" as alleles. With effective questioning and examples, the class comes to understand two key aspects of Mendel's proposed explanation:

- that TWO "factors" determine pea color and when a pea plant inherits one of EACH "factor", the dominant "factor" will prevail
- when a pea plant reproduces, it passes ONE of its "factors" for pea color to its offspring.

Now is the time to introduce how the factors for yellow and green may be represented with alphabetic letter symbols. The capital letter "Y" may be used to represent the dominant factor for yellow color and small letter "y" may be used to represent the recessive factor for green color. Ask students to represent the genotypes of the purebred yellow and purebred green using these symbols, reminding students that TWO factors come together to give the peas their color. After having checked students' work and addressing errors using further questioning, ask students to represent the result of the cross between a purebred yellow and purebred green. Students will see that the offspring phenotype would be 100% Yy. Ask students, "How does this combination account for all the progeny of this cross having only yellow peas?" Finally, challenge students to determine what the expected frequency of yellow and green peas would be if you crossed two heterozygous yellow peas (Yy with Yy).

The predicted 3:1 ratio varies widely from what many groups of two students have observed in their small sample.

But when all groups' data are compiled, the predicted 3:1 ratio appears to far better, but not exactly, fit the data collected by Mendel. This raises the idea of how one knows how much data to collect when doing an investigation. This, in turn, again raises another opportunity to illustrate how data doesn't tell scientists precisely what to think, the difficulties in making sense of data, and how Mendel's contemporaries could reject his ideas regarding heredity.

Only after you have determined that students understand all the concepts addressed thus far should Mendel's law of dominance and law of segregation be formally introduced. The reason for this is that these are simply labels for ideas that require conceptual understanding. Too often teachers introduce vocabulary prior to students having grasped the concept that the terminology represents. This has the unfortunate consequence of directing students' attention to terms and definitions rather than conceptual understanding. Moreover, it misrepresents how scientists create terminology as a shorthanded way to talk about phenomena.

Introducing Dihybrid Crosses

The general approach used above to mentally engage students and promote conceptual understanding prior to introducing terms is also how I introduce dihybrid crosses. I begin by telling students that Gregor Mendel found numerous traits that seemed to be inherited according to his proposed Law of Segregation. However, he wondered whether factors for individual traits, such as pea color and pea shape, influenced each other. In other words, how might a factor for pea color affect the passing down of a factor for another trait? Begin by asking students to come up with an experiment that might answer the following question:

If a pea passes down it's yellow "factor" is it more likely, less likely or equally likely to also pass down the wrinkled "factor"?

Have students think about this individually for a minute or so. Then have them pair with another student and share their ideas. At times, having paired students interact briefly with another pair can be very helpful to groups struggling to propose a cross to address the question. The teacher's role while students think individually is to walk around, observe what they write, and ask questions that spark ideas. When students pair to share their ideas, the teacher's role is to listen intently to students' ideas, their rationale for those ideas, and to ask questions that help students make progress in their thinking.

Afterwards, I conduct a class discussion that emphasizes how proposed ideas by groups would help answer the question. After discussing their ideas, their rationale for proposed crosses, and expected results, I tell students that Mendel first chose to cross plants producing purebred yellow/smooth peas with plants producing purebred green/wrinkled peas. He then took the offspring of this cross, planted them, raised them and cross-pollinated them. I then pose questions like:

- What do you predict will be the result of his first cross?
- What is the significance of using only purebred traits for the first cross?
- What do you predict will be the result of his second cross?

In response to the first question, students will ask whether the smooth or wrinkled trait is dominant. This is a fine time to ask how Mendel would have had to determine the answer to that question. This again places students in a position where they can sympathize with the difficulties Mendel would have faced in his efforts to understand the heredity of peas. After this important point is clear to students, I tell them that the trait for smooth peas is dominant to the trait for wrinkled peas. Students then determine that the first cross would have produced peas that were yellow and smooth.

Tell students that you again have peas on loan from the museum that Mendel collected from this cross (Figure 2). In groups of two have students categorize the kinds of peas they observe. Once the class has agreed on these categories, have students count the number of peas they were given that fit each category. During this time, some groups of students may attempt to determine the expected result using what they have learned earlier about monohybrid crosses. As you walk around monitoring students' work, encourage other groups to do the same and to provide a Punnett square to show the expected results.

Reflecting their prior work with the monohybrid cross, students understand that individual group data may vary widely and should be compiled to provide a more accurate representation of the resultant cross.

Because more than half the observed peas express both dominant traits (approximately 9/16 yellow and smooth), many students will think there IS some influence between color and texture. For this reason, providing sufficient time for students to accurately determine the 9:3:3:1 predicted result of the cross (assuming independent assortment) is CRITICAL. Also important is taking time to break down the two different phenotypes (pea color and pea shape) to help students see that in this dihybrid cross the predicted number of yellow to green peas is still 3:1 and the number of smooth to wrinkled peas is also 3:1. Have students sort Mendel's peas resulting from the dihybrid cross in this manner to help them see that the data approximates a 3:1 ratio pea color and shape. With time and appropriate questions from the teacher, students will make the connection that the traits assort independently. Only after students understand this important insight of Mendel's should the term "Law of Independent Assortment" be introduced. Pose a question to students such as, "What does this law mean?" Students should be able to structure responses that reflect the activities they have just completed, and go well beyond a simplistic textbook definition. Such questions are important for establishing whether students understand and can articulate the idea that traits are transmitted to offspring independently of each other.

Conclusion

Deeply understanding science content requires that students be mentally engaged in making sense of phenomena. This demands that teachers create a classroom climate that promotes critical thinking, problem solving, effective communication, creativity, understanding the nature of science, and other important goals for students. While simply presenting the laws of heredity as if they are self-evident may be done quickly, that approach ends up wasting time because students rarely develop a deep understanding of Mendel's contributions, their significance (and, in time, their limitations) for understanding heredity, and how science works. Having students speculate, design experiments, make sense of data, and struggle to make desired connections are all crucial to deeply understanding science content and the nature of science. However, students will rarely reach these desired understandings without a knowledgeable teacher who asks effective questions that help students draw links, who uses wait-time I and II effectively to encourage students to think, and who uses students' ideas (correct and incorrect) for further inquiry that helps all students understand why particular ideas are accepted while others are abandoned. When teachers do all this, the historical approach described in this

FIGURE 2

Pea sample reflecting a dihybrid cross.

article has great power for promoting a deep understanding of Mendel's contributions and an appreciation for his perseverance, insights and creativity.

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