

Mendel and the Nature of Science

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ABSTRACT

Students often have difficulty understanding inheritance patterns and issues associated with the nature of science as a process. To help address these issues, we developed a unit plan based on Gregor Mendel's well-known research on inheritance patterns among pea plants. The unit introduces students to Mendel's background and the questions he sought to address. Students then conduct their own investigation, using Virtual Genetics Lab II (VGLII) software to attempt to confirm Mendel's results. In the course of completing their investigations, students learn about alternative inheritance patterns to Mendelian genetics. The unit was created in the context of a college introductory biology course but could be implemented in a high school course.

Key Words: History of science (biology); research in biology education; genetics; heredity; molecular genetics; Gregor Mendel.

○ Introduction

Genetics is an important and commonly taught subject in introductory biology courses at both the college and the high school level. Mendelian genetics continues to be among the most commonly taught concepts (Smith & Gericke, 2015), yet students often have misconceptions about inheritance (Mills Shaw et al., 2008). For these reasons, we chose to use Mendelian genetics as context for a unit plan we designed to explicitly teach students about the nature of science (NOS).

Science educators regularly identify NOS as a priority for student learning. The importance of NOS is based on its being a critical component of science literacy (DeBoer, 1991; Rudge et al., 2014). Although there is no single definition of NOS, there are several agreed-upon

concepts. For example, students should be aware of the tentative nature of scientific knowledge, and that scientific knowledge is socially and culturally embedded (Lederman, 2007). Current emphasis on NOS is reflected by its inclusion in the *Next Generation Science Standards* (NGSS) (NGSS Lead States, 2013). Despite the clear importance of NOS, students and teachers have consistently been shown to have inaccurate views of NOS concepts (Lederman, 2007). One of many proposed strategies for improving understanding is to take advantage of the history of science (Matthews, 1994) to provide context for learning about NOS and to legitimize students' ideas about science (Monk & Osborne, 1997).

The three-day unit plan presented here explicitly teaches students about two aspects of NOS: (1) the impact of scientists' backgrounds and (2) that change is an enduring feature of science. The unit plan teaches students about these NOS aspects through the context of Gregor Mendel's classic research on pea plants, specifically its social and cultural dimensions. Students attempt to confirm Mendel's classic

ratios using simulation software to conduct their own investigations. In the process, they learn about alternative inheritance patterns to Mendelian genetics, and gain insight into the nature of science as a process.

○ Historical Basis: Mendel & His Pea Plants

Gregor Mendel (1822–1884) was born in a small Austrian village. He was a talented student as a child and excelled in all subjects. After he completed high school, his physics professor recommended him to the Augustinian monastery in Brunn. There it was determined that

Mendel would be better suited to teaching, as opposed to taking a more pastoral role. After failing the teaching-license exam multiple times, Mendel became a permanent substitute teacher at Brunn

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Modern School, where he conducted his famous pea experiments. Mendel was aware that the same hybrid forms were commonly produced when breeding the same species of plants. However, little was understood about how many hybrid forms existed and, more importantly, about the rules that governed their production (Dunn, 1965). Developing an understanding of how hybrids are produced was important to the community where Mendel lived. Local sheep farmers had an economic interest in being able to predict the offspring of their sheep. In fact, the Sheep Breeding Society of Brunn actively encouraged research on heredity during Mendel's time. It is likely that these local economic interests were an important sociocultural factor in Mendel undertaking his work with pea plants (Westerlund & Fairbanks, 2010).

To gain insight into hybrids, Mendel bred thousands of pea plants and observed several traits, including seed shape, height, and flower color among many others. Many other researchers during this time had conducted similar breeding experiments with plants. However, Mendel's research was unique for its time in that it applied a statistical approach. Mendel's approach to his research was likely a result of his strong background in mathematics and physics (Dunn, 1965). Through his experiments, Mendel established the classic 3:1 and 9:3:3:1 phenotypic ratios (Westerlund & Fairbanks, 2010). In addition, he laid the groundwork for the discovery of the laws of independent assortment and segregation.

Despite the current recognition of the importance of Mendel's work, his ideas were slow to win acceptance in the scientific community (see Franklin et al., 2008). After the initial publication of the pea experiments in 1865, his work was largely ignored until 1900. This oversight is likely due to a variety of factors, chief among them the lack of readership of Mendel's published results and the lack of a statistical basis in his field of study at that time. After 1900, his work was rediscovered by three separate researchers and given its proper recognition. However, aspects of Mendel's work have been controversial. For example, a 1936 paper by R. A. Fisher called into question whether Mendel's results were "too good." Fisher's argument revolves around the statistical unlikelihood, based on chi-square tests, that Mendel would have obtained results that fit so well with his classic ratios. Fisher's article sparked a debate in the literature that persists to the present. That being said, Mendel's contributions have led most current researchers to recognize him as one of the founders of modern genetics.

○ Mendel Unit Plan

This three-day unit was designed for a college introductory biology course and would likely be appropriate for high school biology courses. Fairly flexible, it can be modified to reduce the length or change the focus (specific modification ideas are presented at the end of this article).

Materials

- At least one computer per student group with Virtual Genetics Lab II (VGL II) installed (see Resources)
- Handout with discussion questions for day 1 (see Appendix)
- Edited version of Mendel's original paper (described below)
- Rubric for lab report (see Table 2)

Preparation

One of the primary goals of this unit is for students to engage with Mendel's story to learn about aspects of the NOS. To make the experience more authentic, we like to have students read some of Mendel's original paper on the first day of the unit. We do not want students to become confused or frustrated with understanding the whole paper, particularly since the English translation can be difficult for students to read. Additionally, we do not want to give away Mendel's interpretations of his data, because we want to use Mendel's story to motivate students to conduct their own investigation later in the unit. Therefore, we provide students with a one-page excerpt of the paper that focuses on Mendel's introductory comments and experimental design. Instructors can create their own excerpt that is customized to their teaching goals. Mendel's paper is easily accessed online, free of charge (see Resources).

Procedure: Day 1

During the first class, students are given background information regarding Mendel and the experimental design of his classic pea experiment. This is presented in a short PowerPoint. The presentation covers information about Mendel's life, including his education, occupation, and the area where he lived. In addition, the presentation focuses on the motivation behind Mendel's experiments. For example, students are told that many scientists during Mendel's time were interested in understanding plant hybrids and that the interests of local sheep farmers may have been an economic factor (Westerlund & Fairbanks, 2010).

After the background information has been presented, students are given an excerpt of Mendel's original paper that includes only the portions detailing his experimental design (Westerlund & Fairbanks, 2010). Nothing is included at this point about Mendel's interpretation of his data. After students have read the excerpt, they complete discussion questions in small groups. These questions ask them to reflect on the tentative nature of science in relation to the classification of organisms and Mendel's language in his introductory comments. After discussing the excerpt, students are given a handout with some of Mendel's results (Appendix). They are asked to come up with their own explanations of how the offspring were produced in the numbers found in Mendel's results (Stansfield, 2008). This can serve as an opportunity to assess students' knowledge at the beginning of the lesson. Those students who have experience with Mendelian genetics will have an easier time explaining the data from Mendel's paper. In our own class, most students notice that there are more round and yellow seeds in the example from the Appendix. Most students attribute this to yellow and round being dominant over wrinkled and green. Some students have explained further and included the idea that dominant traits are more commonly found than recessive traits or that dominant traits are stronger or more powerful than recessive traits.

The students are then brought together for a discussion about Mendel's basic experimental design and asked to evaluate some of Mendel's actual data (Stansfield, 2008). Any similarities that can be drawn between the students' explanations and those of 19th-century scientists are used to transition to a more detailed discussion of the beliefs about heredity during Mendel's time. We have included the ideas of Charles Darwin, Alexander Walker, and Jean-Baptiste Lamarck, but other scientists could certainly be discussed here.

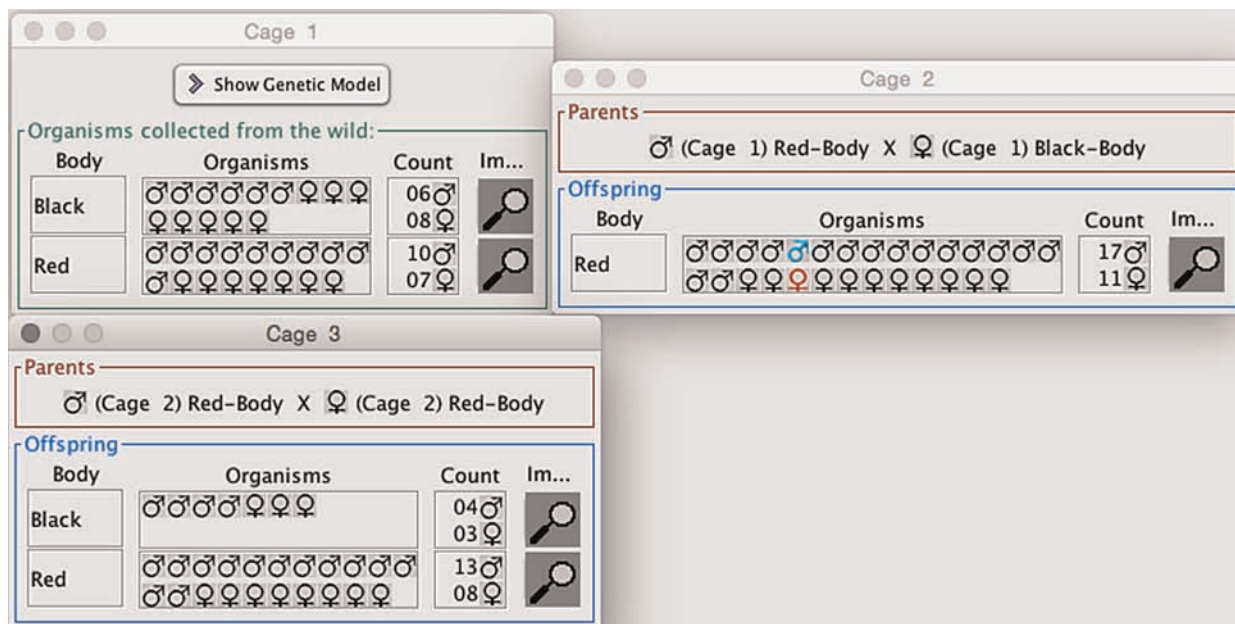


Figure 1. Screenshot from Virtual Genetics Lab II (White et al., 2012). The screenshot shows the results of two crosses. The trait being followed in the crosses is body color.

On the basis of this discussion, the students are asked to reevaluate Mendel's data using the ideas of these 19th-century scientists. While these activities and discussions will lead to several ideas about heredity, the main takeaway is intended to be Mendel's classic 3:1 and 9:3:3:1 phenotypic ratios.

Procedure: Day 2

During the second day of the unit, the students are asked to apply Mendel's ratios to scenarios that illustrate patterns of inheritance different from classic Mendelian inheritance, including incomplete dominance and sex-linked traits (Cartier & Stewart, 2000). The scenarios are presented to students using simulation software called Virtual Genetics Lab II (VGL II; White, 2012). VGL II allows the students to make unlimited crosses using imaginary flies. While there are advantages to using a real organism (e.g., bench science skills), simulation software was selected because simulations have been shown to be particularly effective in the laboratory setting (Rutten et al., 2012). In addition, VGL II allows students to develop problem-solving skills necessary for understanding inheritance in a shorter period and prevents them from finding answers on the Internet, since the flies are fictional. Finally, students gain experience manipulating software, which is an increasingly important skill in science. That being said, it should be emphasized for students that the organisms in the software are not real. Students are not told anything about the inheritance patterns illustrated by the software. The activity puts students in the position of trying to confirm Mendel's classic 3:1 phenotypic ratio in the imaginary flies.

The students complete two scenarios in small groups. In the first, they are given a warm-up activity to help them acclimate to VGL II. This activity consists of the students solving a scenario within the program, in which the students will be working with a single trait that follows classic Mendelian genetics (without their knowledge). The activity asks the students to follow a randomly generated trait through multiple generations of fruit flies. The program generates the trait. Students select which flies to cross and

take notes on these crosses (Figure 1). The goal of the activity is for the students to see that the trait does indeed follow Mendel's 3:1 dominant-to-recessive ratio.

The second scenario follows either incomplete dominance or sex-linked traits. The instructor assigns each group one of the scenarios and does not tell them anything about the inheritance patterns. Students work in their groups to develop their own explanation for their assigned scenario. They are asked to keep notes on the crosses they conduct during their investigation. In addition, students need to take detailed notes on the crosses they choose to make with their flies. As students work through their investigations, the instructor should circulate to answer their questions. The instructor should take care not to tell students what the inheritance pattern is for their assigned scenario.

The students use the results of the simulation to create a lab report. The report requires students to explain their reasoning for the crosses they performed, provide an inheritance pattern, and include an argument for the inheritance pattern based on cross data from their investigation. For the cross-reasoning portion, students discuss the traits they were observing in the flies. They also include a description of the crosses they conducted to explore their assigned scenario. In providing an argument for their proposed inheritance patterns, the students are told to include only data that are necessary to explain the inheritance pattern. In addition, the lab report concludes with a section in which students reflect on NOS. This section focuses on the relationship between the VGL II activity and change in scientific knowledge. Students also report whether or not they think the activity is reflective of actual scientific process.

Procedure: Day 3

On the third day of the unit, the students present the results of their VGL II investigation to the rest of the class. These presentations lead to a discussion of where the study of heredity has gone since Mendel. A mini-lecture covers incomplete dominance and sex-linked traits. The explanation of incomplete dominance includes references to

Carl Correns's work with hawkweed plants. Similarly, the sex-linked-trait explanation delves into Thomas Morgan's work with *Drosophila*. The mini-lecture is intended to fill in gaps in understanding of these inheritance patterns. It also serves to give students another opportunity to reflect on aspects of NOS. After learning about inheritance patterns that are contrary to Mendel's results, students are asked whether they think that Mendel was wrong. This leads into the unique story of how Mendel's work was received by the scientific community and the controversy after its acceptance. The discussion concludes with students answering questions regarding the reception of Mendel's work and the implications of his story for change in science knowledge.

○ Learning Objectives

The unit plan addresses several aspects of the NGSS. The specific crosscutting concepts and life-sciences core idea covered by the unit plan are included in Table 1. In addition to these aspects, the unit plan also covers several science and engineering practices, including analyzing and interpreting data, constructing explanations, and engaging in arguments from evidence. These practices are primarily covered through the VGL II investigation. Students collect data on the offspring produced by their crosses with the imaginary flies. They need to interpret the data in order to explain the inheritance pattern operating in their scenario. For the lab report, the students are asked to create an explanation of the inheritance pattern they observe in their scenario. The lab report requires students to provide evidence that supports their explanation, illustrating evidence-based argumentation.

In addition to the learning objectives above, the unit focuses on two NOS objectives from the NGSS. The first is "Science Is a Human Endeavor" (NGSS Lead States, 2013: appendix H). The NGSS point out that multiple cultures have contributed to

science, and that scientists' backgrounds and their field of study influence their scientific interpretations. The first day of the unit, students learn about Mendel's background. Part of this discussion includes information about how the culture surrounding Mendel influenced his work. In addition, students answer discussion questions from the perspective of various scientists who worked during Mendel's time. This provides examples of scientists explaining the same phenomenon (inheritance) in different ways. The second NOS objective is "Scientific Knowledge Is Open to Revision in Light of New Evidence." During the first half of the unit, students learn about Mendel's classic 3:1 and 9:3:3:1 ratios. The VGL II investigation tasks students with testing these ratios. The investigation introduces students to two non-Mendelian inheritance patterns in sex-linked traits and incomplete dominance. Since these inheritance patterns contradict Mendelian inheritance, this gives students concrete examples of how scientific knowledge can change over time.

○ Assessment

Students are assessed summatively on their understanding of the NOS and life-sciences instructional goals through a lab report (for example rubric, see Table 2). In addition to writing up the report, students are required to share their findings through informal class presentations during day 3 of the unit. Formative assessment is handled informally throughout the unit. During day 1, students' interpretations of Mendel's data provide the instructor with information on the students' level of understanding of Mendelian genetics coming into the unit. For day 2, during part 1 (the practice scenario) of the VGL II investigation, the instructor circulates, listening to students and answering questions. The instructor can identify areas in which the students are having difficulties, in both the genetics content and the software. The instructor can then focus on these areas before setting students loose on part 2 of the activity.

Table 1. Crosscutting concepts and life-sciences core idea from the *Next Generation Science Standards* covered by the unit.

Crosscutting Concept	Part of Unit
Patterns: Observed patterns of forms and events guide organization and classification, and they prompt questions about relationships and the factors that influence them.	After students complete multiple crosses of imaginary flies in the Virtual Genetics Lab II (VGL II) software, they look for patterns in the offspring produced.
Cause and effect: Mechanism and explanation. Events have causes, sometimes simple, sometimes multifaceted. A major activity of science is investigating and explaining causal relationships and the mechanisms by which they are mediated. Such mechanisms can then be tested across given contexts and used to predict and explain events in new contexts.	For a lab report, students attempt to explain the patterns identified in VGL II. Students share their conclusions in group presentations. These presentations lead to a discussion of the current scientific explanations of sex-linked traits and incomplete dominance.
Life Sciences Core Idea	Part of Unit
Inheritance of traits: The instructions for forming species' characteristics are carried in DNA. All cells in an organism have the same genetic content, but the genes used (expressed) by the cell may be regulated in different ways.	The VGL II investigation puts students in the position of trying to confirm Mendel's classic 3:1 phenotypic ratio. Students are asked to explain what is happening in one of two scenarios that involve incomplete dominance or sex-linked traits. This provides students with some examples of how the expression of genes can vary.

Table 2. Example rubric for student lab report for their VGL II investigation.

Abstract _____	Introduction _____
<p>A 3-sentence description of your investigation. Include the trait investigated and a brief mention of your methods and proposed inheritance pattern. This section is intended to give your reader a brief overview of your study.</p> <p>0 No abstract provided.</p> <p>2 Abstract provided but it does not effectively (or completely) introduce the inheritance pattern to the reader.</p> <p>4 Abstract is provided and includes a clear and complete explanation of the inheritance pattern.</p>	<p>A paragraph (at least 5 sentences) that explains the trait you investigated and your research question(s). Also, include some explanation of how you intend to answer your research question. You want to bring your reader up to speed on your study and catch their interest.</p> <p>0 No introduction is provided.</p> <p>2 Introduction is provided but does not include a description of the research question or the methodology.</p> <p>4 Introduction is provided and clearly explains the research question. However, the methodology is not included or is not clear.</p> <p>6 Introduction is provided and is clear and complete.</p>
Methods _____	Results and Discussion _____
<p>A summary (at least 5 sentences) of the steps you took to answer your research question. You should not include every cross you completed. Focus on explaining how you decided which flies to cross in order to understand the inheritance pattern working on your trait.</p> <p>0 No methods are provided.</p> <p>2 Methods are provided but are incomplete.</p> <p>4 Methods are provided and complete, but part or all of the methods are unclear and/or all crosses are included.</p> <p>6 Methods are provided in full and are clearly described. Only general descriptions of the crosses conducted are provided (not all crosses).</p>	<p>A paragraph (at least 5 sentences and one figure) explaining the inheritance pattern you developed from investigating your trait. Include descriptions of the crosses conducted that provide evidence supporting your pattern. The cross descriptions should include Punnett squares. Think of this section as an evidence supported argument for your pattern.</p> <p>0 No results and discussion section is provided.</p> <p>2 Results and discussion are included, but the inheritance pattern is not supported by data and there is no figure.</p> <p>4 Results and discussion are included and the inheritance pattern is supported by data, but a figure is not included and/or irrelevant data are presented.</p> <p>6 Results and discussion are provided including a figure and the inheritance pattern is supported by data. Irrelevant data are not included in the report.</p>
Nature of Science _____	TOTAL SCORE out of 30 _____
<p>A paragraph (at least 5 sentences) that discusses two “nature of science” tenets: (1) there are no absolute truths in science, and (2) science is continually changing. Is this lab activity reflective of these tenets? Is this activity reflective of the practice of actual scientists?</p> <p>0 No discussion of the nature of science is included.</p> <p>2 The authors discuss the nature of science but do not make specific mention of their investigation.</p> <p>5 The authors discuss the nature of science and make specific mention of their investigation.</p> <p>8 The authors discuss the nature of science, and make specific mention not only of their investigation, but also of the extent to which it is similar to or different from the work of actual scientists.</p>	<p>NOTE: You must participate in the presentation of your findings to receive full credit for this assignment.</p>

Additionally, students have the opportunity to try out different strategies for solving the genetics problems in part 1 in a low-risk environment. There are no grades for part 1, and the problems in it are familiar to students from previous activities. This gives students an opportunity to improve their approach before beginning their actual investigation in part 2 of the VGL II activity.

○ Activity Modifications

The following modifications can be made to the unit to customize it for an instructor's particular needs:

- Instead of writing a lab report, students could create posters that feature sections similar to those described for the lab report. If

time allows, instructors could also add statistical analysis to the lab report assignment. Students could test their inheritance-pattern hypotheses using chi-square tests. For example, once students have determined that they are observing traits that follow incomplete dominance, they can calculate χ^2 to compare data collected from VGLII to expected data. VGLII is capable of calculating χ^2 within the software. On the final day of the unit, students could share their results by means of a poster session. Both posters and statistical analysis would help bring the unit in line with the AP Biology curriculum (College Board, 2012).

- To enhance the historical aspects of the unit, a section could be added to the lab report or poster in which students explain whether their results agree or disagree with Mendel's findings. Students could further explain whether, in light of their results, they see value in learning about Mendel.
- The VGL II investigation could be expanded or changed, depending on the instructor's learning goals. Students could be asked to complete more and/or different scenarios. VGL II is capable of generating flies that follow most inheritance patterns.

○ Conclusion

Preliminary use in our college-level classroom suggests that the unit might be effective in improving students' NOS views. We collected data from eight students through an established NOS evaluation instrument, the Student Understanding of Science and Scientific Inquiry Questionnaire (Liang et al., 2008), given before and after the unit. In addition, interviews were conducted after the unit. Results showed improvements in students' NOS views related to the tentative nature of science and social and cultural influences on science. It should be noted that by "tentative," we are referring to the idea that scientific knowledge is durable but responsive to new evidence (McComas, 2004). Students' interview responses indicated that the discussion of different interpretations of inheritance by 19th-century scientists and the controversy surrounding Mendel's work were effective in illustrating the impact of scientists' backgrounds on their interpretations. The interview responses also indicated that discussion of the economic pressures of Mendel's home region, and their influence on Mendel's work, may have made students consider the importance of culture in science. We consider the unit presented here an excellent introduction to inheritance and Mendelian genetics. The unit would be well suited as the beginning of a larger genetics unit. From use in our own class, we have found that the VGL II investigation portion of the unit provides just enough challenge to create dissonance among students without frustrating them. Therefore, we recommend that instructors consider using the unit plan presented here as a tool for improving their students' NOS views and introducing inheritance.

Resources

Virtual Genetics Lab II is available for free at <http://vgl.umb.edu>.

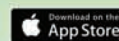
Mendel, G. (1865). Experiments in plant hybridization. Read at the meetings of February 8th and March 8th, 1865. Available online, for example at <http://www.mendelweb.org/Mendel.html>.



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Appendix: Mendel's Data Handout (Day 1)

Part 1. Below are some data from Mendel's original paper published in 1865.

1. 7324 seeds were obtained in the second trial year. Among them were 5474 round or roundish ones and 1850 angular wrinkled ones. (Note: The parent generation that produced these plants were plants with round seeds and plants with wrinkled seeds.)
2. The fertilized seeds were round and yellow like those of the parents. The plants raised from them yielded seeds of four sorts, which frequently presented themselves in one pod. In all, 556 seeds were yielded by 15 plants, and among these were
 - 315 round and yellow,
 - 101 wrinkled and yellow,
 - 108 round and green, and
 - 32 wrinkled and green.

(Note: The parent generation that produced these plants were plants with round yellow seeds and plants with wrinkled and green seeds.)

Discussion Questions

- Do you notice any patterns in the data?
- Can you draw any possible conclusions regarding heredity in these pea plants from the data? What do you think has led to the variation in the traits (seed shape and color) of these pea plants?

Part 2. Choose one of the scientists below to discuss with your group members.

- If you were Charles Darwin, how would you interpret the data?
- If you were Jean-Baptiste Lamarck, how would you interpret the data?
- If you were Alexander Walker, how would you interpret the data?

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