

Using Digitized Museum Collections to Investigate Population Variation in Plants

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ABSTRACT

*Understanding the causes and consequences of variation among populations is fundamental for understanding the process of evolution via natural selection. To support students in noticing, questioning, and investigating variation in wild populations, we describe an introductory investigation that used digitized museum plant specimens as the primary focus. The activity illustrates how digitized museum collections can be used to introduce natural phenomena into the classroom, even without physical access to a museum. Through measuring plant specimens and examining patterns in data, students had opportunities to discuss how to obtain accurate measurements, handle noisy data, and request data that would be helpful for further investigation of the patterns they observed. In our example, we focused on one flowering plant, the royal penstemon (*Penstemon speciosus*), which varies in size across environmental gradients: larger plants are found at lower elevations, and smaller ones on the highest peaks, a pattern commonly observed in nature. Overall, this lesson led students to observe this pattern and wonder about the environmental constraints affecting phenotypes. We provide examples of the kinds of activities that could follow our lesson to provide students with opportunities to connect their ideas to intraspecific variation, a key component for understanding evolutionary processes.*

Key Words: population variation; natural selection; intraspecific variation; collections; science practices.

○ Introduction

Natural history museums serve as the foundation for much of what we know about biodiversity, natural variation, and evolution of life on Earth (Evans et al., 2010; Cook et al., 2014). They are also powerful learning environments, allowing visitors to closely interact with plant and animal specimens and to observe and learn about natural phenomena. However, these important cultural and historical institutions are an often underutilized resource for classroom learning (Hiller et al., 2017), likely due to lack of access and availability of collections for use by teachers and learners in undergraduate

and K–12 classrooms. Additionally, while many educators may be familiar with the large natural history museums in the nation's most populous regions, there are many smaller, regional collections throughout the United States. One such regionally focused institution is the Museum of Natural History at the University of Nevada, Reno, which features the biodiversity of the Great Basin. Like larger natural history museums, however, these regional collections are primarily accessible to those who are able to visit; at our museum, our primary medium for communicating science is through person-to-person interactions with museum educators or scientists, or through direct, in-person exploration of our collections.

Recognizing that our collections were available only to the subset of public visitors and researchers able to physically visit the museum, the curators decided to make our collections more accessible by photographing specimens and putting the images online. One collection with extensive online presence is our plant collection (25,000+ specimens), which is publicly available via a large database of digitized museum plant specimens, the Intermountain Herbarium Network.¹

With the rise of digitized collections, museum specimens are available to a wider and more diverse audience and can serve as accessible and productive, regionally focused phenomena for authentically engaging learners in scientific practice. To demonstrate how digitized collections can be used to foster authentic and productive science learning, this article presents an introductory lesson using digitized plant specimens to promote understanding of variation among populations, or intraspecific variation. We also illustrate how our lesson provided students with opportunities to begin constructing an understanding of Disciplinary Core Ideas (DCIs) and engage in the Scientific Practices outlined in the *Next Generation Science Standards* (NGSS Lead States, 2013).

¹ We are actively imaging our entire plant collection (100,000+ specimens); as of publication, 25% of our collection is available online through the Intermountain Region Herbarium Network, <http://intermountainbiota.org/>, along with images from many other Intermountain collections. Similar regional networks exist throughout the United States; for a full list, see <http://symbiota.org/docs/seinet/>.

○ Problematising Intraspecific Variation Using *Penstemon speciosus*

Inspired by the early work of Jens Clausen, David Keck, and William Hiesey, we chose to use royal penstemon (*Penstemon speciosus*), an attractive and widespread perennial herb, as the focal species for students to investigate. In an article published in *The American Naturalist*, Hiesey, Clausen, and Keck (1942) described how ecotypes of plant species differed by climate, focusing on plants growing along the coasts, valleys, and mountains of California. They observed that while the same plant species could be found in all of these environments, their subgroups, or populations, varied in obvious characteristics, such as height, when growing under different environmental conditions. This pioneering work was the first to clearly demonstrate how plant form (or phenotype) can evolve in response to local environmental conditions, a fact that is now well accepted. This phenomenon of phenotypic variation among populations is widespread, and every region of the world will have examples of the same plant species looking very different while growing in different environments. In the case of our focal plant, royal penstemon, it varies in height from 15 to 30 cm when growing across climates and elevation ranges spanning from the western coast of the United States, such as Oregon and California, to the valleys and mountain ranges that make up the Sierra Nevada, the Cascades, and the various ranges in Nevada. It was this variation in height among plant populations that we wanted students to observe, question, and explore in their investigations with digitized plant specimens.

Student misunderstandings of what variation is and the role it plays in evolutionary processes are common (Nehm & Reilly, 2007), but intraspecific variation is a key component for understanding adaptation and natural selection (e.g., Mayr, 1982; NGSS Lead States, 2013; Tibell & Harms, 2017). Because variation in phenotype can be tied to genetic variation, environmental variation, and the interaction between the two, observing variation in wild organisms provides opportunities to pose questions about how environment affects plant phenotype, but also inheritance, mutation, and the role of sexual reproduction in ensuring variation within species. These ideas are integral to student learning in NGSS and are related to each of the four Life Science Disciplinary Core Ideas (HS-LS1, HS-LS2, HS-LS3, HS-LS4).² Thus, one introductory lesson that provides students with opportunities to observe and question a phenomenon related to intraspecific variation within a familiar system could lead students to begin constructing an understanding of key concepts related to natural selection, a key principle important for biological understanding.

○ Lesson Objectives

- Provide opportunities for students to
 - observe patterns in digitized historical plant specimens;
 - generate ideas to explain why patterns may occur; and
 - design investigations to test, evaluate, and revise ideas.

- Foster discussions about the reasoning and decision-making processes that scientists use to study natural phenomena in the field and in the laboratory.

We implemented this lesson with first-year undergraduate students during orientation week, and this was one of the first science lessons they participated in as college students on our campus. Since they were recent high school graduates and because observing and explaining phenomena plays a key role in NGSS, our discussion will primarily focus on connections to the science practices and high school life science disciplinary core ideas. The materials needed to implement follow-up investigations are variable and depend on the ideas and experiments students suggest for exploring observed patterns in the plant collections. At a minimum, for the introductory lesson, groups of two to four students will need a ruler and/or measuring tape, printed digitized images of eight historical plant specimens (see Figure 1), and a data collection sheet with questions intended to support students in generating ideas about the phenomenon they observe (see Appendix). We chose eight specimens of royal penstemon from our museum collections so that they represented a range of heights, site locations across climates and elevation ranges, and variance in dates collected (1940–2016). The materials were given to student groups and they were asked to observe the kinds of information provided on the scanned image: a color scale; the species name; date, location, and elevation of the collection site; and name of the person who collected it. Next, they were tasked with measuring the height of the plants, using the measuring tape provided.

Measuring digitized specimens led to productive arguments concerning methods for producing data and questions concerning sampling methods used in the field. Argumentation is a key scientific practice described in NGSS, and in the process of investigating phenomena, scientists often argue not only about how to evaluate ideas, but also how to evaluate methods of investigation. In this case, students argued and asked questions about how to obtain accurate measurements: should they measure from the ends of the plant roots to the top of the terminal leaf, or should they approximate where the soil level was on the stem and measure from there? That led to another argument among some groups: would approximation of soil level provide accurate data or not? Should they measure each plant three times and then calculate the average of their

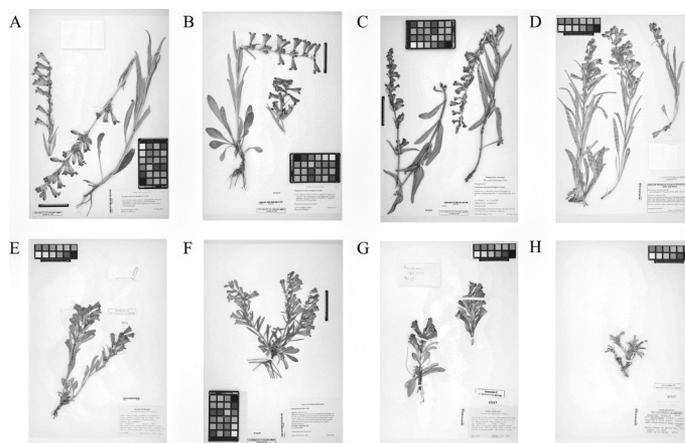


Figure 1. *Penstemon speciosus* images used in this investigation, organized (A–H) by elevation of collection site, from lowest elevation to highest. Color images can be found at <https://scholarworks.unr.edu/handle/11714/7359>.

² For a more thorough explanation of how ideas related to mechanisms for evolution connect to other biological ideas, see Apodaca et al. (2019) and Passmore et al. (2016).

measurements? With students in each group measuring in different ways, this led to a noisy data set, representing a more realistic version of the data scientists produce. Based on student conversations, it proved fruitful that we did not provide them with explicit directions for how to measure the plants, since it led to discussions for evaluating how they might produce more accurate measurements. In practice, scientists investigating plant size in pressed specimens have used strings to measure the absolute length of pressed plants. The string is run along the length of the plant, not including the roots, such that they are able to account for any curves in the main stem. Then it is the string that is measured. Although we did not provide string to the students, given the flexibility of measuring tape, teachers could include that in the set of materials available for each group.

Through the course of measuring the plant specimens, students also began discussing the sampling methods used to collect the plants originally. They wondered whether the collections were representative of the species, whether there were biases in who was collecting and where, whether the previously collected samples were trustworthy, and how their data set might change if the provided specimens were more comprehensive. With respect to our plant specimens, there is some bias in where and when the plants were collected: plants collected at higher elevations tend to be older than those collected at lower elevations, which does affect the representativeness of samples. Interestingly, however, with minimal guidance, the measurement activity led to questions and discussions that are related to problems that scientists often grapple with in the field and in the laboratory, about how to best produce data and how to handle noisy data. Importantly, students were learning valuable scientific skills, such as determining which tools to use for measurement and how to use them, through the course of investigating a phenomenon, rather than the skills being taught independently of a productive investigation.

The data sheet provided to students (see Appendix) scaffolded the observation process by providing a table for students to keep track of their measurements, and to note any patterns they observed in the height and elevation of where the plant was collected. It was through examining this table that students were able to see the phenomenon: there is an inverse relationship between elevation and plant height. From there, students began to ask questions such as *why* is there variation in plant height across elevations? “Asking questions” is another key scientific practice described in NGSS, and it is the means through which scientists problematize the observed phenomenon (Phillips et al., 2018). In this case, students were problematizing the concept of intraspecific variation.

○ Explaining Intraspecific Variation in Royal Penstemon

Asking “how” or “why” questions provides avenues for creating mechanistic, model-based explanations of a phenomenon (Passmore et al., 2014). Models are sets of ideas, based on evidence, that describe relationships between components of systems (Passmore et al., 2014; Gouvea & Passmore, 2017), and modeling is a third scientific practice in NGSS, central to the development of scientific knowledge (Giere, 1988; Passmore & Gouvea, 2017). Models are tested and refined through the course of investigations, and thus it is important for students to be given opportunities to discuss their initial models, based on their own prior knowledge, that could explain why they observed the inverse relationship between elevation and

plant height (“constructing explanations” is a fourth NGSS scientific practice), and to then use those initial models to plan and carry out investigations – a fifth scientific practice outlined in NGSS.³ The guiding worksheet also gave students space to outline their initial models and explanations for what is causing the observed phenomenon to occur, and we also asked them what data they would want to help them better understand why plant height varied from low to high elevations. Their initial ideas and data requests could then be used in subsequent lessons to plan and carry out investigations and revise and/or extend their model in service of constructing an explanation of the phenomenon. Table 1 provides a summary of ideas and data requests, based on responses from 64 students.

When examining students’ initial model ideas and explanations (see Table 1), we noticed an interesting pattern: they identified factors that affect individual plants, such as resource limitation (DCI LS2; lines 1, 2, 4, and 8), disturbance (DCI LS2; lines 3 and 7), or plant age (DCI LS1; line 9), but omitted from their initial models and explanations connections to ideas related to inheritance and variation (DCI LS3) and evolution (DCI LS4). With guidance, students may come to understand that there are three possibilities for explaining the inverse relationship between plant height and elevation: (1) genotypes are identical across all royal penstemon plants, and the observed size differences are environmental only (hypothesized explanations in Table 1); (2) observed size differences are genetic only, and result solely from a higher survival of small plants at high elevations and greater survival of tall plants at lower elevations; or (3) plant size is determined through genotype × environment interactions. These three possible explanations are those that were considered by Clausen, Keck, and Hiesey (1948), who tested them by using a simple but powerful experimental design: they collected seeds from across coastal, valley, and mountain environments; grew them together in common locations at multiple elevations; and measured plant size and survival. Through their experiments, they observed that plants collected from high elevations were always small, no matter where they grew, and vice versa for low-elevation plants, indicating genetic determinants for this phenotypic trait.

Table 1. Initial model ideas generated by students for explaining height differences in royal penstemon.

1. Water levels across elevations, water quality
2. Oxygen and carbon dioxide levels, air quality
3. Weather and climate patterns could influence plant growth (includes relative humidity, length/severity of winter conditions, rainfall, average temperature)
4. The type of soil and its quality, including soil composition, nutrient availability, nitrogen levels, erosion patterns
5. Population of organisms that feed on plants is large, keeping the plants shorter
6. Steepness of slope where plant was collected
7. History of wildfire
8. Other vegetation, competition for space
9. Plant age

³ For a discussion of how the NGSS practices interrelate, see Passmore et al. (2017).

Further, they observed that low-elevation plants failed to survive in high-elevation locations, and high-elevation plants failed to survive in low-elevation locations. When grown in their local environmental conditions, the plants were able to grow, flower, and set seed during their respective growing seasons. Together, these data indicated that the observed differences among populations not only were genetically determined but were adaptive traits.

Clausen, Keck, and Hiesey's results were a major breakthrough in plant research and today form the foundation for many plant ecology studies. The same factors they tested presumably affect our populations of royal penstemon; that is, the environmental conditions in which royal penstemon populations live (coastal, valley, subalpine, alpine) determine which phenotypes are advantageous or not, which affects genotypes within plant populations. Given enough time, students could consider experimental designs to test this phenomenon with a set of seeds and growing conditions; they could examine the model of Clausen, Keck, and Hiesey to determine the extent to which it relates to their own; and/or they could test model ideas with freely available simulations, including PhET Simulations (<https://phet.colorado.edu>) and NetLogo (Wilensky, 1999). Importantly, however, students should develop an understanding of intraspecific variation and the underlying gene \times environment interactions that cause it.

○ Conclusion

As we have shown, digitized museum collections can provide accessible and productive opportunities for students to engage in authentic scientific practices and to develop important skills, including observation, hypothesis formation, and testing based on a model. This introductory activity provided multiple moments for students to grapple with methods for producing data, which subsequently led to argumentation, asking questions, and also elements of modeling and constructing explanations. Additionally, students' observations can lead to deep engagement with the study of natural selection in the wild.

We continue to digitize specimens in our museum collection, including laying the framework for linking other elements of our collection together by digitizing images of pollen samples from pressed plants and pollen collected from legs and bodies of pinned insects. These important links to the natural world that we are creating through digital imagery will allow teachers to bring specimens, preserved for years, into the classroom and will provide students with opportunities to observe hidden plant–animal interactions. Moving forward, we will continue to include these resources on our museum website, and we welcome discussion with other educators, across K–12 and undergraduate and graduate spaces, who are doing similar work.

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Appendix: Investigating Royal Penstemon: Student Handout

Look at the eight images provided to you. What information is included on the pressed and scanned specimens? Why is this information important?

Observe the plant specimens. What do you notice about the plants?

Now you will begin measuring the plants using the materials provided to you. As you measure, fill-in the data table below. Then, share your data on the class datasheet.

DATA TABLE	
Elevation (m)	Plant Height (cm)

What pattern(s) do you notice in the class data set?

What do you think may be causing the pattern(s)?

What data would you want to help you better understand why the pattern(s) appear in royal penstemon?

What questions do you still have?

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