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Recipe for Developing High-School Research Projects Illustrated by a Student's Interpretation of Historical Metal Casting

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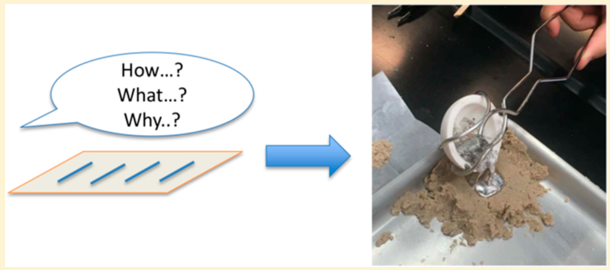
ABSTRACT: Incorporating research activities at the secondary-school level is an effective method to teach science; however, students and teachers may feel intimidated when trying to identify a suitable research topic. Ideas may be obtained from short articles in periodicals or newspapers to allow students to design their own experiments and interpret data. To illustrate how high-school research projects can be developed from such sources and accomplished with simple techniques and tools, a student-directed project inspired by historical metal-casting methods is described. References to key steps in the process of scientific inquiry are included to demonstrate how simple ideas can yield research questions.



KEYWORDS: *High School/Introductory Chemistry, First-Year Undergraduate/General, Interdisciplinary/Multidisciplinary, Inquiry-Based/Discovery Learning, Enrichment/Review Materials, Student-Centered Learning*

■ INTRODUCTION

At Princeton International School of Mathematics and Science (PRISMS), a STEM-centered high school, all students must complete a two-year research program during their junior and senior years. This requirement was based on an assumption that the best way to learn science is to do science: "Ultimately all scientific knowledge is rooted in the experiences of the learner, and the processes involved in scientific investigation and organization are an integral part of what science is... an essential feature of science education is that the precollege student participate in these processes."[1]

The goal at PRISMS was for students to participate in research projects with an unknown outcome. It was expected that the research be student-directed under the guidance of a research mentor, but it was not required that it be wholly student-conceived.[2] Research work was independent, however, in the sense that each student was responsible for searching and reading the background literature, suggesting and conducting experiments, interpreting data, and communicating results. Students were provided more guidance and oversight in the initial phases of their research but were transitioned toward independence and an active role in generating new ideas from experimentation and research. Research experiences not only teach experimental and analytical skills but also develop life skills such as time management and perseverance.

Though many believe that research is feasible in high school,[3−7] there are limitations in time, resources, and expertise that can hinder widespread implementation in more schools. For instance, many students struggle with finding a research question that can be addressed at the secondary-school level and may feel that conducting research is out of reach. To illustrate how high-school research projects may be accomplished using simple techniques and tools, a recent student project is described with reference to the iterative model of inquiry proposed by Harwood.[8−10] Harwood specifies a series of tasks that a scientist engages in, though not necessarily in a prescribed order, all centered on "questions" (Table 1). Though 10 discrete activities are

Table 1. Harwood Model

Harwood Activity[9,10]	Description
Questions	Asking questions (how, why, what, and when) is central to all inquiry
Defining the problem	Establishing the specific focus of a project or activity; a broad research project may be composed of several smaller questions
Forming the question	Posing a question for which an answer may be found
Investigating the known	Reading the literature
Articulating the expectation	Formal or informal, stated or unstated hypothesis
Carrying out the study	Devising (and revising) experiments and collecting data
Examining the results	Determining validity of data
Reflecting on the findings	Drawing conclusions from the experiments and synthesizing with the known
Communicating with others	Formal presentations, posters, and papers; lab notes; discussions
Observing	Observations are made at various steps in the process, including Questions, Investigating the known, and Carrying out the study

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defined by Harwood, there is often overlap, for example, between "Defining the problem" and "Forming the question",[9] and questions and observations can occur at any point in the process (such observations and questions are highlighted throughout the following discussion of the project).

FINDING A QUESTION

One of the most difficult tasks for high-school students is finding a topic. Periodicals or a newspaper's science section can be used to stimulate curiosity and suggest potential questions. For instance, students at PRISMS who were interested in chemistry but had no specific ideas were given brief articles from publications such as *Chemical & Engineering News*[11−14] and other sources[15] to read. It was such an article[12] about the Making and Knowing Project[16−18] that motivated the investigation into metal casting. The historical aspect captured the student's interest and provided the opportunity to discuss the use of chemistry in the analysis and preservation of cultural artifacts.

INVESTIGATING THE KNOWN

The Making and Knowing Project is a research effort initiated by the Center for Science and Society at Columbia University to study the connections between art and science. Researchers have recently concentrated on an early modern French manuscript represented by the serial number BnF Ms. Fr. 640 (its call number at the National Library of France, Bibliothèque Nationale de France),[19] interpreting the text, identifying materials involved, and reconstructing the described processes.[17,18] This 16th century manuscript belongs to the "book of secrets" genre and is essentially a how-to manual with instructions on many different topics ranging from tree planting to dye making.[17] It is considered unique because it contains the experiences and annotations of the anonymous French author−practitioner, including notes about both failed and successful trials. The manuscript BnF Ms. Fr. 640 resembles a lab notebook and could be used to demonstrate to students the value of reporting all experimental attempts, both failures and successes.

DEFINING THE PROBLEM

Rather than emphasizing realistic historic recreations, the student chose to use methods inspired by the French manuscript to investigate the impacts of different binders on castings of tin and lead. The manuscript describes several molding materials, including ox bone, oyster shells, and coal,[20−22] as well as different binders such as egg white or elm root boiled in either vinegar or wine.[23−25] For convenience, quartz sand was used as the molding material, and elm root was replaced with readily available slippery elm bark powder, a North American native plant.[18] As a high-school research project, wine was not an option, and a decision was made to replace it with 10% aqueous ethanol; it was also felt that using a standard solution was important for reproducibility of the study.

FORMING THE QUESTION AND ARTICULATING THE EXPECTATIONS

The question was simple: Is it possible to tell what binders were used in a sand mold by examining the metal cast afterward? The student hypothesized that binding agents and molding materials would leave traces on the metal castings that could be observed by microscopic analytical techniques. By attempting simple sand casting, she aimed to learn if any "chemical fingerprints" remained that could be used to identify or characterize a method of casting. As the project progressed, an attempt was made to artificially age some of the lead castings in order to model investigations into corrosion and degradation processes of historical artifacts.[26−29]

CARRYING OUT THE STUDY

Metal Casting

All materials were used as received without further purification. White quartz sand was obtained from Acros (AC61235); lead shot, granular tin, 95% ethanol, 30% hydrogen peroxide, and sodium chloride were obtained from Flinn Scientific; and slippery elm bark powder was obtained from Starwest Botanicals. Common household white vinegar (5% acidity, equivalent to a 5% acetic acid aqueous solution) was used, and egg white was obtained directly from fresh eggs when needed. As experiments were conducted on a small scale, egg whites from one or two eggs at a time were used.

To prepare sand molds, white quartz sand was mixed with either water or a binder: egg white, slippery elm bark powder boiled in vinegar, or slippery elm bark powder boiled in aqueous ethanol. Slurries of slippery elm bark were prepared by boiling 10 g of slippery elm bark powder in 150 mL of either vinegar (equivalent to a 5% acetic acid aqueous solution) or aqueous ethanol (10% concentration by volume).

The binders and sand were combined in an approximate 1 to 10 ratio by volume and mixed in a large beaker using a spatula. The sand molds were determined ready for casting if the sand−binder mixture could retain an impression in its surface. This was examined by the squeeze test described in the manuscript: "Having thus moistened the sand in order to give it a nice hold, though it still came apart easily."[18,30]

The mixture was poured onto a stainless-steel pan used as a casting box. The bottom of a square bottle (Figure 1) was

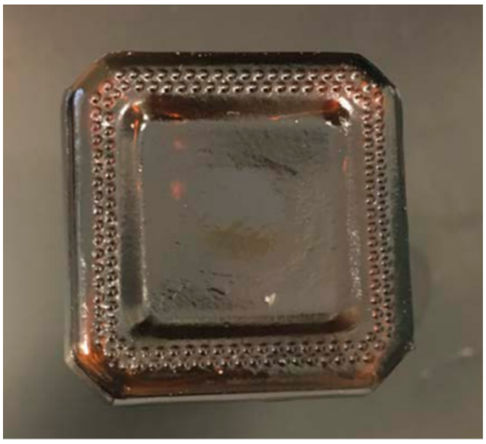

Figure 1. Bottom of the 3 × 3 cm bottle used as pattern for molds.

depressed about 0.5 cm into the sand−binder mixture to create an impression about 3 by 3 cm. The pattern chosen provided both gross (e.g., raised edges) and fine (e.g., repeating dots) details for observation and comparison.

Metal (25 to 30 g of either tin or lead) was heated in a crucible over a butane burner (Lenk Model 65 Laboratory Burner). When molten, the metal was poured from crucible

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Figure 2. Metal casting using sand molds.

into the cavity left by the bottle in the sand (Figure 2). The castings were left to cool in air. When the metal was cool to the touch (after approximately 30 min), castings were removed from the sand, washed with water, and then visually and microscopically inspected.

The casting techniques, though simple in theory, required practice to obtain detailed castings. The formation of a skin, most likely PbO,[31] was noted on molten lead prior to pouring into the sand mold. Small quantities of this film were not observed to affect the formation of detailed castings. In some casting attempts, relatively large holes formed on the surface of the castings, likely the result of water in the sand boiling as molten metal was poured into the mold. As an example of the "Observing" activity, it was noted that sand molds that used egg white as a binder turned black in regions contacted by the molten metal, but no other physical changes were noted in the molds.

Accelerated Corrosion and Aging

Two samples of lead with good detail were selected and exposed to either sodium chloride solution (to mimic immersion in seawater) or hydrogen peroxide solution (to induce oxidation). A lead sample prepared from casting in the slippery elm bark and vinegar binder sand mold was immersed in 0.6 M NaCl aqueous solution for 48 h; this concentration was selected after an "Investigating the known" activity to determine the typical salinity of seawater. A lead casting prepared in the slippery elm bark—alcohol binder sand mold was immersed in 30% aqueous H_2O_2 solution for 48 h. Both samples were removed and cleaned with ethanol in an ultrasonic bath before surface analysis.

Surface Examination

Surfaces were examined by optical microscopy using a Boreal Zoom Stereomicroscope (10−30× magnification) with incident light. Photographs under the microscope were taken using a Carson HookUpz 2.0 Universal Smartphone Optics Digiscoping Adapter and a smartphone. Although we found that optical microscopy was adequate for surface analysis, the student was able to negotiate access to a scanning electron microscope (SEM) at a neighboring university. (Although many students do not typically have access to sophisticated equipment, they may find opportunities to access advanced equipment from professional researchers or may replace analytical instruments by creative use of smart phones,[32−34] Arduinos,[35−37] and 3D printers.[38,39]) Surfaces were characterized by scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) using a FEI Quanta 200 FEG Environmental-SEM equipped with an Oxford INCA Synergy 450 EDS system and an Oxford X-Max 80 mm^2 silicon drift detector. These were operated under high vacuum (2.57 × 10^{-6} Torr) and 10.00 or 15.00 keV electron-acceleration voltage. Samples for SEM analysis were cleaned with ethanol in an ultrasonic bath and air-dried prior to mounting on stubs with conductive carbon tape.

■ HAZARDS

Prudent laboratory practices were observed, and protective gloves and eye protection were worn at all times. The metals described have relatively low melting points that are readily attainable in the lab (tin melts at 232 °C, and lead melts at 327 °C). Though tin metal is considered nonhazardous, elemental lead is a possible human carcinogen and is harmful if swallowed or inhaled; lead should not be heated above 400 °C. To avoid breathing dust and fumes, the metals were heated and poured in a fume hood to minimize exposure. Minimal amounts of metal were heated at a time, using crucibles and tongs designed for melting metals. Hands were washed thoroughly after handling the materials.

■ EXAMINING THE RESULTS AND REFLECTING ON THE FINDINGS

Observations from Metal Casting

Repeated trials taught that the consistency of the sand is important to control. If too wet, the sand stuck to the bottom of the bottle used to create the mold; if too dry, the sand did not maintain the shape of the impression. When water was used with no added binder, it was difficult to obtain a detailed impression in the sand. This highlighted the need to use a binding agent in order for the sand to maintain its shape. When either egg white or slippery elm bark slurry was used, the sand felt stickier and maintained the shape of the impression better, though some cracks were observed in the sand.

Tin and lead metal produced castings with different characteristics; the tin samples generally exhibited greater luster than the lead samples, and the tendency of lead to tarnish was apparent in the duller appearance of some lead samples. No significant visual differences were apparent between tin or lead casts made using egg white or slippery elm bark powder as binder in the sand mold. By both visual inspection and optical microscopy, the two lines of dots around the border of the bottle were evident in both the tin and lead castings prepared from molds with binder (Figure 3a). In contrast, no evident detail was observed in castings made from the water-only sand molds (Figure 3b).

Several general defects occurred in metal castings and were evident by both the naked eye and optical microscopy (Figure 4). These observations gave rise to new questions (i.e., the student recorded "why did the cast form bubbles" in her lab notes) that necessitated background reading to understand the

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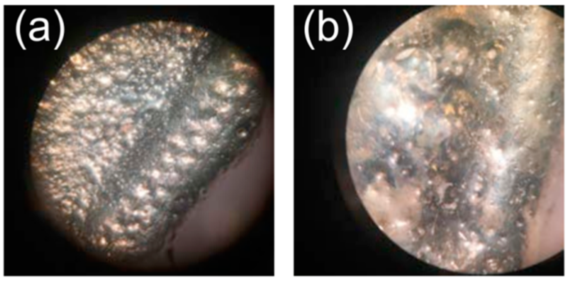

Figure 3. Optical microscopy (15×) of edges of tin castings made using sand molds with (a) egg white−ethanol binder or (b) no binder. Details from the bottle are evident in tin castings made using sand molds with egg white−ethanol binder but not in castings prepared in sand molds with no binder.

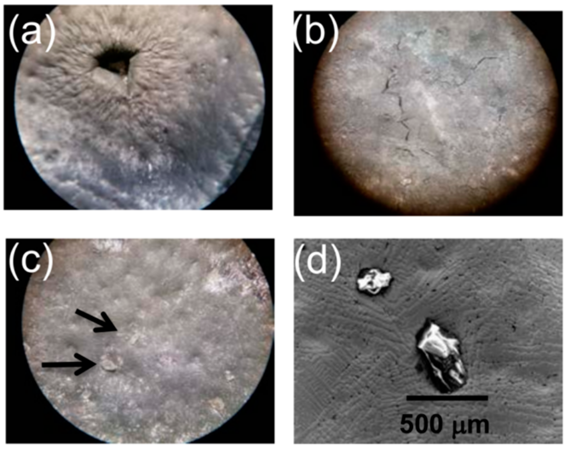

Figure 4. Optical-microscopy (30×) images revealing (a) blowhole in lead casting prepared from a sand mold using egg white as a binder, (b) cracks in lead casting prepared from a sand mold using no binder, and (c) sand grains (indicated by arrows) embedded in lead casting prepared from a sand mold using slippery elm bark boiled in ethanol as a binder. (d) Scanning electron micrograph (63×) of embedded sand grains in lead casting prepared from a sand mold using slippery elm bark boiled in ethanol as a binder.

possible mechanisms that can occur. This demonstrates an iteration of the Harwood Model from "Observing" to "Questions" to "Investigating the known". It was found that pores and blowholes form when liquids trapped in the casting sand boil, trapping vapors in the molten metal (Figure 4a),[40] and cracks appear when the metal cools to room temperature, and the metal's volume decreases (Figure 4b).

Although standard optical microscopy was sufficient to observe details on the castings, the opportunity to utilize scanning electron microscopy (SEM) revealed a surface feature on the tin casting prepared in the egg white−sand mold (Figure 5); significant amounts of carbon, oxygen, chlorine, and sodium were observed by EDS analysis. Thus, "Observing" led to "Questions" requiring further "Investigating the known" and another iteration of the Harwood method.

As similar features were not observed on castings prepared by other methods, it was hypothesized that this was organic residue derived from the egg white used as the binder. Carbon and oxygen can be attributed to the proteins and carbohydrates that are the primary components (after water) of egg white. Small amounts of salts and minerals are also found in egg white, with chlorine, sodium, potassium, and sulfur the most abundant elements present.[41] Additional examples will be

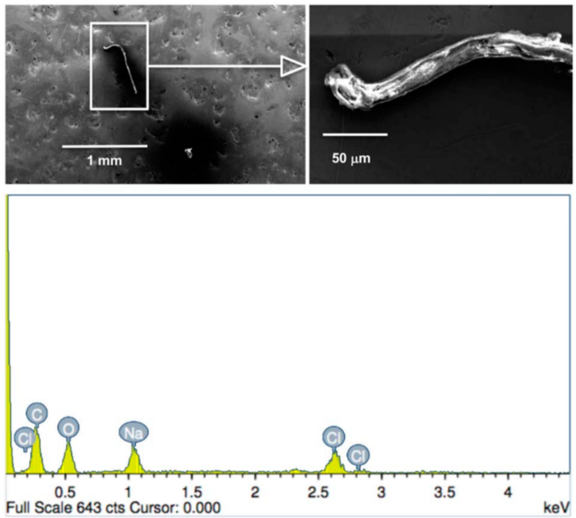

Figure 5. Scanning electron micrograph (37×) of tin casting prepared in an egg white−sand mold showing a stringy artifact. EDS analysis (638×) revealed the presence of C, O, Cl, and Na.

necessary to draw a definitive conclusion; this is a potential branch point for initiating another research question and a new "Defining the problem" activity.

Observations from Aging and Exposure to Corrosive Conditions

Corrosion in seawater is typically a combination of chemical reactions and anaerobic corrosion;[42] lead may be oxidized to an oxide that can react with NaCl to yield lead chlorides[43] or converted to sulfate salts that are susceptible to bacteria.[44] The test samples were only immersed in brine for a short period and with no added sulfate or calcium ions as might be expected in seawater. In the experimental samples, no major physical changes in the lead surface were noted after 48 h. The limited number of samples prevented drawing any conclusions, but this could provide a starting point for another project.

Following 48 h in hydrogen peroxide, substantial visible surface changes were evident in the lead sample (Figure 6).

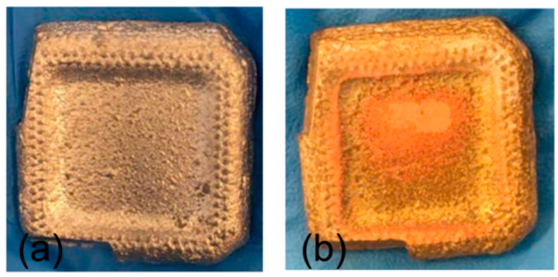

Figure 6. Lead metal casting (a) before and (b) after 48 h immersion in 30% H_2O_2.

This observation initiated another new "Investigating the known" activity to learn about potential oxidation products of lead. The reddish-brown appearance of the casting was in agreement with formation of oxides such as PbO and Pb_3O_4, which range in color from light yellow to red, and brown PbO_2.

High-school research is often dependent on the academic school year and limited by the school-day schedule. For this project, the student mounted the metal castings on SEM stubs for another SEM session that had to be postponed, and the

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labeled samples were left in a drawer during summer vacation. When school resumed in the fall, there were notable differences in the appearance of the lead castings (Figure 7).

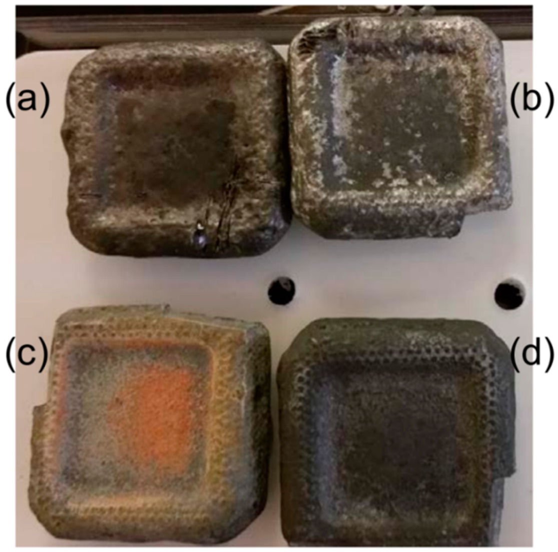

Figure 7. Lead castings after aging under typical indoor conditions (6 months) made in (a) sand mold with water, (b) sand mold with slippery elm bark−alcohol binder, (c) sand mold with slippery elm bark−alcohol binder after 48 h exposure to 30% H_2O_2, and (d) sand mold with slippery elm bark−vinegar binder after 48 h exposure to NaCl(aq).

As the student had maintained detailed lab notes identifying each sample, further analysis of the changes was possible. Lead castings prepared from molds using only water (Figure 7a) or slippery elm bark−vinegar (Figure 7d) as the binder were dull gray in color after 6 months, though the latter appeared more uniform in appearance. Acetic acid is known to accelerate corrosion of lead,[26,45] and it is possible that the vinegar in the sand molds led to formation of lead acetates in addition to lead oxides. In contrast, the sample prepared using the slippery elm bark−ethanol binder incompletely tarnished and still retained some luster (Figure 7b). Further investigation would be necessary to corroborate this observation; this is another potential branch point for a defining a new research problem and articulating new expectations (and could provide the inspiration for another student's project).

The lead casting that had been oxidized with hydrogen peroxide prior to storage was multicolored (Figure 7c), possibly because of the formation of blue-gray lead carbonates, as has been reported for the corrosion of lead printing letters in a museum collection.[26] The multidimensional appearance of the different-colored compounds was pronounced under optical-microscope examination (Figure 8).

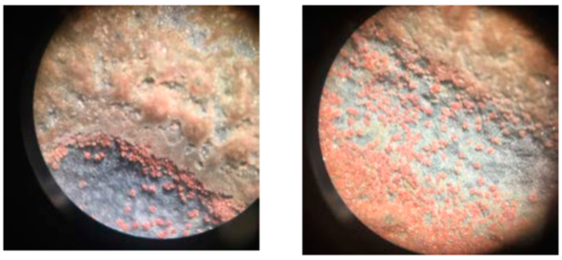

Figure 8. Appearance of lead casting prepared from a sand mold using slippery elm bark−alcohol binder 6 months after oxidation with 30% H_2O as observed by optical microscopy at 30×. A whitish-gray crust is evident along the edge. A blue-gray compound formed over a large portion of the surface.

COMMUNICATING WITH OTHERS

In any science research experience, it is important that students gain experience in formal and informal communications. As part of PRISMS' program, research students participate at the end of each semester in a school-wide research symposium, in a either formal oral or poster presentation. The audience is primarily their classmates and faculty. In addition, students have had the opportunity to participate in a local student research poster presentation at the IEEE Integrated STEM Education Conference (ISEC),[46] a conference wherein the audience comprises STEM educators as well as professional scientists and engineers.

It is important that informal discussions and lab records are not ignored as part of science communication. For the metal-casting project, the student had several face-to-face and email discussions with participants in the Making and Knowing Project at Columbia University. These were invaluable in clarifying some of the source annotations and providing historical background. For the duration of the two-year project, an electronic lab notebook was maintained using OneNote (Microsoft) software. It is important to stress to students that lab books should do more than just document experimental methods and results; they should also capture reflections and questions, as in the following excerpt:

> *This time, I tried the method of using egg white. I mixed the sand evenly with the binder in a big beaker first, and then poured them into the mold box after it passes the squeeze test. One thing is that this mixture matches the description of squeeze test easily while water mixture does not. It might be caused by the method of mixing or properties of water. This time, the sand felt more sticky and easy to maintain its shape. Despite something like a bubble at the bottom of the cast, the final product was astonishingly detailed, especially it even contained the two lines of little dots. This big difference was not expected, because when the original bottle was pushed into sand, the sand also cracked at few places, and details like the small dots was not seen. The part of sand that is near the tin turned black, probably because the egg white is burned.*

The value of lab notes is not immediately obvious to students when the experiments are fresh in their minds. However, without the detailed notes made in the spring, the discovery of differences after 6 months of storage would not have been possible.

REFLECTING ON THE PROJECT

The student's original expectations and questions were directed to examining if it was possible to determine what binders were used in sand molds to cast lead and tin metal. The simple answer was no; for the samples prepared, there were no major differences between the different metals or binders, either by the naked eye or optical microscopy, though the need for a binder in the molds was readily obvious. It should be emphasized to students that all data, whether supportive of a hypothesis or not, are useful because they teach something and may suggest additional avenues for research. For example, the slippery elm bark−ethanol molds appear to

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offer protection against oxidation; further experimentation and surface analysis may help in understanding any differences. Such observations illustrate to students how research projects can evolve by the generation of new questions as data is collected and emphasize the iterative process described by the Harwood method.

This discussion illustrates how student research projects can be developed from various sources and do not need to be overly technical or complex; simple equipment and techniques may be used, and questions can be straightforward. Early research provides an opportunity for students to investigate questions for which the answers are (as yet) unknown. At the secondary-school level, student research can be driven by curiosity and "what happens if" questions; the journey, as represented by the Harwood method, is more important than the destination.

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Notes

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REFERENCES

(1) Abrams, E. Talking and Doing Science: Important Elements in a Teaching-for-Understanding Approach. In *Teaching Science for Understanding*; Elsevier: Amsterdam, 2005; pp 307−323, DOI: 10.1016/B978-012498360-1/50013-1.

(2) Mohlhenrich, E. R.; Samsonau, S. V.; Spencer, R. P. Integrating Science through Authentic Research in Secondary Schools. *Proceedings of the 2018 IEEE Integrated STEM Education Conference (ISEC)*, Princeton, NJ, March 10, 2018; IEEE, 2018; pp 14−21, DOI: 10.1109/ISECon.2018.8340465.

(3) Hannum, M. S. A Suburban Magnet High School's Perspective on Authentic Research Experiences for Students: An Overview of Research Pathways and a Discussion of the Benefits. In *The Power and Promise of Early Research*; ACS Symposium Series *1231*; American Chemical Society: Washington, DC, 2016; pp 49−58, DOI: 10.1021/bk-2016-1231.ch003.

(4) Sogo, S. G. Advanced Chemical Research at Laguna Beach High School: High School Seniors Engaged in Authentic Laboratory Research. In *The Power and Promise of Early Research*; ACS Symposium Series *1231*; American Chemical Society: Washington, DC, 2016; pp 33−47, DOI: 10.1021/bk-2016-1231.ch002.

(5) Kennedy, B. J. Integrating Advanced High School Chemistry Research with Organic Chemistry and Instrumental Methods of Analysis. *J. Chem. Educ.* **2008**, *85* (3), 393.

(6) Murray, D. H.; Obare, S. O.; Hageman, J. H. The Future of Early Research. In *The Power and Promise of Early Research*; ACS Symposium Series *1231*; American Chemical Society: Washington, DC, 2016; pp 247−254, DOI: 10.1021/bk-2016-1231.ch013.

(7) Hapkiewicz, A. Authentic Research within the Grasp of High School Students. *J. Chem. Educ.* **1999**, *76* (9), 1212.

(8) Robinson, W. R. The Inquiry Wheel, an Alternative to the Scientific Method. A View of the Science Education Research Literature. *J. Chem. Educ.* **2004**, *81* (6), 791.

(9) Harwood, W. An Activity Model for Scientific Inquiry. *Sci. Teach.* **2004**, *71*, 3.

(10) Harwood, W. S. A New Model for Inquiry. *J. Coll. Sci. Teach.* **2004**, *33*, 1−5.

(11) Arnaud, C. Paper Sensor Measures Respiration Rate. *Chem. Eng. News* **2016**, *94* (16), 8.

(12) Everts, S. Reviving Ancient Recipes. *Chem. Eng. News* **2015**, *93* (31), 35−37.

(13) Bourzac, K. Spinning a Triboelectric Yarn. *Chem. Eng. News* **2018**, *96* (2), 7.

(14) Morone, M. I. F. Materials on the Move. *Chem. Eng. News* **2018**, *96* (9), 36−42.

(15) Newton, J. Lego brick microfluidics. *Chemistry World*, Jan 30, 2018. https://www.chemistryworld.com/news/lego-brick-microfluidics/3008517.article (accessed March 2019).

(16) The Making and Knowing Project. *Columbia University*. https://www.makingandknowing.org/ (accessed March 2019).

(17) Smith, P. H. In the Workshop of History: Making, Writing, and Meaning. *West 86th A J. Decor. Arts, Des. Hist. Mater. Cult.* **2012**, *19* (1), 4−31.

(18) Smith, P. H. Historians in the Laboratory: Reconstruction of Renaissance Art and Technology in the Making and Knowing Project. *Art Hist.* **2016**, *39* (2), 210−233.

(19) *Recueil de recettes et secrets concernant l'art du mouleur, de l'artificier et du peintre [Collection of recipes and secrets concerning the art of the moulder, the artificer and the painter]*, BnF Ms. Fr. 640. http://gallica.bnf.fr/ark:/12148/btv1b10500001g.r=.langEN (accessed March 2019).

(20) A minimal edition of BnF Ms Fr 640, Folio 084v. *The Making and Knowing Project*. https://cu-mkp.github.io/2017-workshop-edition/texts/p-084v_tl/ (accessed March 2019).

(21) A minimal edition of BnF Ms Fr 640, Folio 083r. *The Making and Knowing Project*. https://cu-mkp.github.io/2017-workshop-edition/texts/p-083r_tl/ (accessed March 2019).

(22) A minimal edition of BnF Ms Fr 640, Folio 049r. *The Making and Knowing Project*. https://cu-mkp.github.io/2017-workshop-edition/texts/p-049r_tl/ (accessed March 2019).

(23) A minimal edition of BnF Ms Fr 640, Folio 082r. *The Making and Knowing Project*. https://cu-mkp.github.io/2017-workshop-edition/texts/p-082r_tl/ (accessed March 2019).

(24) A minimal edition of BnF Ms Fr 640, Folio 085v. *The Making and Knowing Project*. https://cu-mkp.github.io/2017-workshop-edition/texts/p-085v_tl/ (accessed March 2019).

(25) A minimal edition of BnF Ms Fr 640, Folio 087v. *The Making and Knowing Project*. https://cu-mkp.github.io/2017-workshop-edition/texts/p-087v_tl/ (accessed March 2019).

(26) Storme, P.; Jacobs, M.; Lieten, E. Research on Corrosion of Lead Printing Letters from the Museum Plantin-Moretus, Antwerp. *Procedia Chem.* **2013**, *8*, 307−316.

(27) Neff, D.; Reguer, S.; Dillmann, P. Analytical Techniques for the Study of Corrosion of Metallic Heritage Artifacts: From Micrometer to Nanometer Scales. In *Corrosion and Conservation of Cultural Heritage Metallic Artefacts*; Elsevier, 2013; pp 55−81,.

(28) Arnaud, C. H. Saving Shipwrecks. *Chem. Eng. News* **2007**, *85*, 45−47.

(29) Wang, Q.; Strekopytov, S.; Roberts, B. W.; Wilkin, N. Tin Ingots from a Probable Bronze Age Shipwreck off the Coast of

DOI: 10.1021/acs.jchemed.7b00917
J. Chem. Educ. XXXX, XXX, XXX−XXX

Salcombe, Devon: Composition and Microstructure. *J. Archaeol. Sci.* **2016**, *67*, 80−92.
(30) A minimal edition of BnF Ms Fr 640, Folio 118v. *The Making and Knowing Project*. https://cu-mkp.github.io/2017-workshop-edition/texts/p-118v_tl/ (accessed March 2019).
(31) Campbell, J. The Melt. In *Castings*; Elsevier: Oxford, 2003; pp 1−16, DOI: 10.1016/B978-075064790-8/50018-8.
(32) Kuntzleman, T. S.; Jacobson, E. C. Teaching Beer's Law and Absorption Spectrophotometry with a Smart Phone: A Substantially Simplified Protocol. *J. Chem. Educ.* **2016**, *93* (7), 1249−1252.
(33) Gee, C. T.; Kehoe, E.; Pomerantz, W. C. K. K. K.; Penn, R. L. Quantifying Protein Concentrations Using Smartphone Colorimetry: A New Method for an Established Test. *J. Chem. Educ.* **2017**, *94* (7), 941−945.
(34) Grasse, E. K.; Torcasio, M. H.; Smith, A. W. Teaching UV−Vis Spectroscopy with a 3D-Printable Smartphone Spectrophotometer. *J. Chem. Educ.* **2016**, *93* (1), 146−151.
(35) Jin, H.; Qin, Y.; Pan, S.; Alam, A. U.; Dong, S.; Ghosh, R.; Deen, M. J. Open-Source Low-Cost Wireless Potentiometric Instrument for PH Determination Experiments. *J. Chem. Educ.* **2018**, *95* (2), 326−330.
(36) Kubínová, Š.; Šlégr, J. ChemDuino: Adapting Arduino for Low-Cost Chemical Measurements in Lecture and Laboratory. *J. Chem. Educ.* **2015**, *92* (10), 1751−1753.
(37) Arrizabalaga, J. H.; Simmons, A. D.; Nollert, M. U. Fabrication of an Economical Arduino-Based Uniaxial Tensile Tester. *J. Chem. Educ.* **2017**, *94* (4), 530−533.
(38) Stewart, C.; Giannini, J. Inexpensive, Open Source Epifluorescence Microscopes. *J. Chem. Educ.* **2016**, *93* (7), 1310−1315.
(39) Davis, E. J.; Jones, M.; Thiel, D. A.; Pauls, S. Using Open-Source, 3D Printable Optical Hardware To Enhance Student Learning in the Instrumental Analysis Laboratory. *J. Chem. Educ.* **2018**, *95* (4), 672−677.
(40) Campbell, J. Moulding. In *Complete Casting Handbook*; Elsevier: Oxford, 2015; pp 797−819, DOI: 10.1016/B978-0-444-63509-9.00015-7.
(41) Mine, Y.; Zhang, H. Egg Components in Food Systems. In *Biochemistry of Foods*; Eskin, N. A. M., Shahidi, F., Eds.; Elsevier: Amsterdam, 2013; Vol. *1*, pp 215−241, DOI: 10.1002/1521-3773(20010316)40:6<9823::AID-ANIE9823>3.3.CO;2-C.
(42) Phull, B. Marine Corrosion. In *Shreir's Corrosion*; Elsevier: Amsterdam, 2010; pp 1107−1148, DOI: 10.1016/B978-044452787-5.00046-9.
(43) Lyon, S. B. Corrosion of Lead and Its Alloys. In *Shreir's Corrosion*; Elsevier: Amsterdam, 2010; Vol. *1*, pp 2053−2067, DOI: 10.1016/B978-044452787-5.00098-6.
(44) Kahanov, Y.; Ashkenazi, D. Lead Sheathing of Ship Hulls in the Roman Period: Archaeometallurgical Characterisation. *Mater. Charact.* **2011**, *62* (8), 768−774.
(45) Niklasson, A.; Johansson, L.-G.; Svensson, J. The Influence of Relative Humidity and Temperature on the Acetic Acid Vapour-Induced Atmospheric Corrosion of Lead. *Corros. Sci.* **2008**, *50* (11), 3031−3037.
(46) *Program Book of the IEEE Integrated STEM Education Conference (ISEC 2017)*, Princeton, NJ, March 11, 2017.

DOI: 10.1021/acs.jchemed.7b00917
J. Chem. Educ. XXXX, XXX, XXX−XXX