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In the Classroom

The Transmutation of Wax: A Lesson in Experimental Design and Controls

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The activity described here forces the students to compare alchemy with chemistry...

The need for controls in experimental science is a difficult concept for many science students to grasp. To illustrate its importance, we developed an activity in which students, acting in the role of alchemists, perform an uncontrolled transmutation experiment. When their experiment yields a surprising result, the students are forced to recognize the critical role that a control plays in experimental design. The activity is constructivist in nature and engaging for students. Additionally, it offers the opportunity to introduce multicultural issues and topics from the history of science.

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Introduction

Recently, we taught *Integrated Science 1* (Science 110) at Salisbury State University. Science 110 is a general science course designed primarily for elementary education majors as a contribution to the Maryland Collaborative for Teacher Preparation (MCTP), an NSF-funded Collaboratives for Excellence in Teacher Preparation (CETP) project (NSF DUE 9255745). One of the stated objectives of the MCTP project is to train upper-elementary and middle-school math and science teachers by modeling different teaching styles. Prominent among these is a constructivist approach [1, 2]. As described by Brooks and Brooks [1], "Learning from this perspective is understood as a self-regulated process of resolving inner cognitive conflicts that often become apparent through concrete experience, collaborative discourse, and reflection."

A goal of *Integrated Science 1* is to engender an appreciation of, and understanding for, what science is and how science is done. One effective constructivist strategy forces students to confront and resolve previously held misconceptions through hands-on activities. The activity described here forces the students to compare alchemy with chemistry (a pseudoscientific approach with a scientific approach) by asking them to perform an uncontrolled experiment. While most of the students initially see no problem with the experimental design as it is presented to them, cognitive conflict results when they attempt to resolve the unexpected results of the experiment. The intended outcome of the investigation is that students discover for themselves the importance of controls in the design of experiments. This concept is presented as a distinguishing feature of scientific investigation. Since the development of this activity, it has been used successfully in several other classes targeted at nonscience majors.

Overview of the Activity

Prior to the class meeting, wax ingots are cast by the instructor. Some of these are prepared with seeds or other small living things embedded within so as to be invisible upon casual inspection. (Instructions for preparing the ingots are provided below.) During the class, students are asked to perform an experiment as the alchemists might have done, attempting to produce life in an ingot of wax. Each student is given a single ingot of the precast wax and asked to attempt to create life within it by any treatment of their choice. Experimental treatments involving cutting or melting the ingots are

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prohibited. Written assignments describe the experiment performed, along with observations and interpretation of results.

During the next class meeting, general discussion focuses on the students' experiences:

What treatment did you try?

Did you succeed in creating life?

How do you know?

How would you recognize something that is alive?

Was your experiment a scientific one?

How could it have been improved?

Once these issues have been raised, students are allowed to break open the wax ingots and examine them more closely. Upon opening them, some of the students will discover that their ingots contain seeds. Further discussion centers on whether it is legitimate to conclude that any of the experimental treatments were responsible for producing life in the wax. While none of the students are likely to believe that they actually created life, they should understand that because their experiments lack controls, and because they did not thoroughly investigate their starting material before the experiment was performed, it is not possible to rule out the possibility that their treatments produced the seeds on the basis of their results alone. Table 1 illustrates the activities and their objectives.

Student Handout

The Transmutation of Wax

A. Introduction

Put yourself in the place of an alchemist any time before 1500 A.D. In your work, you routinely face some difficulties. Not only is the local population suspicious of your activities, but the local government has branded you an outlaw. The ecclesiastical establishment claims you consort with the devil. Because of this, you must work in secret. You dare not keep records of your work in plain English. Instead, you craft a secret code that only you can understand. You have heard enough stories and anecdotes to make you believe in transmutation, a process of converting one substance

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Table 1. Activities/Objectives for the laboratory *The Transmutation of Wax*

Activity	Objective
Prelaboratory discussion	to reveal student preconceptions and address multicultural issues, to identify what parts of an experiment make it scientific
Individual Assignment (at home experiment)	personal experience with experimental design and recording observations, demonstrating the flexibility of experimental design
Group Assignment 1	introduction to group work and group dynamics
Group Assignment 2	analyzing data, discussion of experimental design, critical thinking and theory testing
Summary of Results	Introduce statistics and importance of reproducibility of results
Postlaboratory discussion	highlight control experiments and how experimental design influences outcomes

into another. Written sources, cloaked in codes developed by others, have told you how to prepare medicines, paints, soaps, and even gold from common materials. You have verified some of these protocols yourself by experimentation and magic.

The tale below describes an alchemical experiment. For centuries, this tale might have been the best chemistry text available. As you read it, ask how it compares with experiments you have performed in a science class. How does the coded language of the alchemist and this description of an experimental protocol compare with a modern lab manual? (A key to the code is found at the end of the story.)

B. A Tale

The sun had not yet risen above the horizon, but the master and the student were ready. After many months of prodding by the student, the old man had finally agreed to let him test his skills. The student had spent many days in preparation for the test. Earthen bowls, covered with magical symbols and pictographs that only the master could read, were precisely arranged according to the signs revealed by the stars and the planets in the heavens. All the others who could read and interpret the symbols had passed now into distant memory. If the student succeeded at his task, the ancient would pass on

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this knowledge to him. After years of apprenticeship, he might become the next guardian of the master's secrets.

A frail urn, covered with *dragon's breath*, was set atop a large stack of kindling. The urn was filled with the sweetest spring water, carefully drawn by the student under the full moon. The student took hold of a mighty orange bowl, filled it with the *tears of vestal virgins* and gently floated it on the water in the urn. Carefully, he poured fragrant *oleum of stone* upon the wood, soaking it completely. With appropriate ritual, a red jar of *dragon's breath* was shattered on the wood. Awaiting the sun, the student went into a trance, speaking incantations in an ancient, long forgotten tongue. Opening his eyes, the student removed a lump of *gray stone* from its bath of *virgin's milk* and made wide passes over the urn. The master watched with expectant eyes, but revealed no sign of approval. The incantations were completed and a somber dance performed. Between two pieces of *aromatic rosin* coated with *powdered unicorn horn*, he crushed the *gray stone*. At the instant the sun broached the horizon, pieces of *gray stone* tumbled into the water. After a brief moment of anticipation the student's eyes widened in horror. Red and lavender flames spewed from the water followed by a great flash of light. The wood was consumed by fire.

The master nodded, heaved a sigh and returned to his hut. In the morning he would have to begin the search for a new apprentice.

The above story actually describes a plausible, if dangerous, chemical reaction that could be performed in the laboratory today. Do you recognize it? Substitute the following modern equivalents for the code words in the story to see what chemical reaction the student was carrying out. Wax = *dragon's breath*, diethyl ether = *tears of vestal virgins*, kerosene = *oleum of stone*, potassium = *gray stone*, mineral oil = *virgin's milk*, gelatin = *powdered unicorn horn*, glass = *aromatic rosin*.

C. Individual Assignment

Today, you are asked to perform an alchemical experiment. You will attempt to create life within an ingot of ordinary wax. Recall that spontaneous generation of life was accepted as scientific fact by the alchemists. Your instructor will distribute one wax ingot to each member of the class. As an alchemist, it is your responsibility to decide upon and carry out a treatment you think might result in the transmutation of the wax

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into a living thing. The only restriction placed on you is that **you may neither cut nor melt the wax during your experiment**. Be creative!

In any experiment, observations are essential. During the course of your experimental treatment, **record your thoughts and ideas about the treatment and its potential effectiveness**. Include the rationale behind your choice of treatments. Critically examine your experimental design. Consider not only what observations to make, but why those are good choices. (For example, a chemist working in a pharmaceutical lab is not likely to record the phase of the moon under which the work is performed, but an oceanographer is likely to do so. Have both made good choices?) **Bring both your ingot and the written analysis of your experiment to your next class.**

Group Work

Your instructor will organize the class into small working groups. As a group, you should discuss and answer the following questions:

1. What experimental treatments were used by you and your labmates on the wax?
2. What does it mean to be alive? Are you sure you would recognize life in the wax if you saw it?
3. Which treatments were effective? How can you tell?
4. If life *is* discovered inside any of the wax ingots, can you safely assume that the experimental treatment produced it? Why or why not?
5. What changes would you make in the design of your experiment if you were to repeat it? Why?
6. Can you think of a way to examine the inside of the wax ingot without destroying it?

Notes on Teaching the *Transmutation of Wax*

A discussion of alchemy and how it differs from chemistry will be helpful as an introduction to the activity. Such discussion is likely to reveal interesting misconceptions about both the relationship between science and pseudoscience and about alchemy and its place in the history of science (see Section VI below). The

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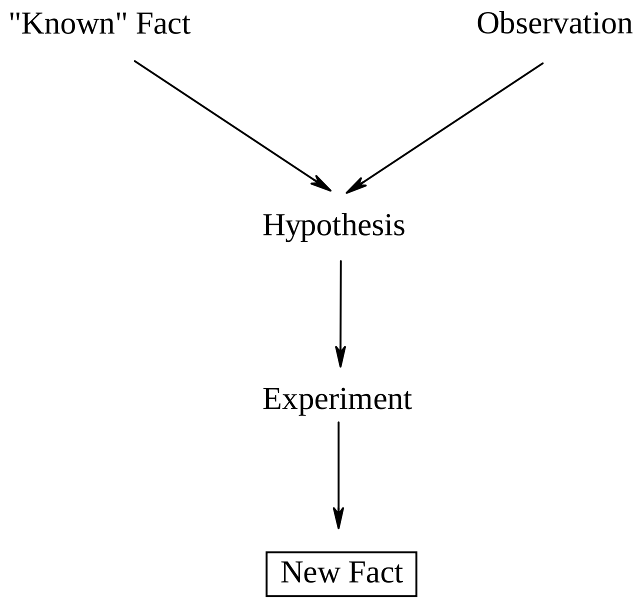

FIGURE 1. THE SCIENTIFIC METHOD IS USUALLY PORTRAYED AS A LINEAR APPROACH TO LEARNING A NEW FACT. OBTAINING A RESULT IS PORTRAYED AS NORMAL. DISCUSSION OF ALCHEMY ALSO PROVIDES A VEHICLE FOR INCORPORATING MULTICULTURAL ISSUES, SINCE ALCHEMY WAS PRACTICED IN A VARIETY OF CULTURES AND ETHNIC SETTINGS.

Students should be encouraged to take an active interest in the wax and not let it sit, forgotten, at the bottom of a backpack. In one or two short paragraphs, they should record the rationale behind their experiment and explain why it might have some chance for success. Their observations should also be included. These might include deformation of shape, details of the experimental conditions, and color changes. In performing their experiments, students should be asked if what they are doing is a good example of how science is done—the scientific method. Examples of student experiments carried out most commonly in our classes are: 1) burying the wax as an analogy to planting a seed, 2) chanting or prayer, 3) watering the wax and weighing it to measure uptake, 4) incubating the ingot in sunlight, 5) carrying the wax about in a pocket as an analogy to nesting, 6) putting the wax into the fish tank (life presumably having started in the ocean), and 7) incubating it atop the television set (the ultimate source of life, according to this student). Typically, students are taught that the scientific method has four parts; it begins with observation or known fact and is followed by hypothesis, experiment, and development of theory (Figure 1). In reality, science is an iterative process in which all of these activities relate to one another (Figure 2). In this activity, students start from theory and work back to observation.

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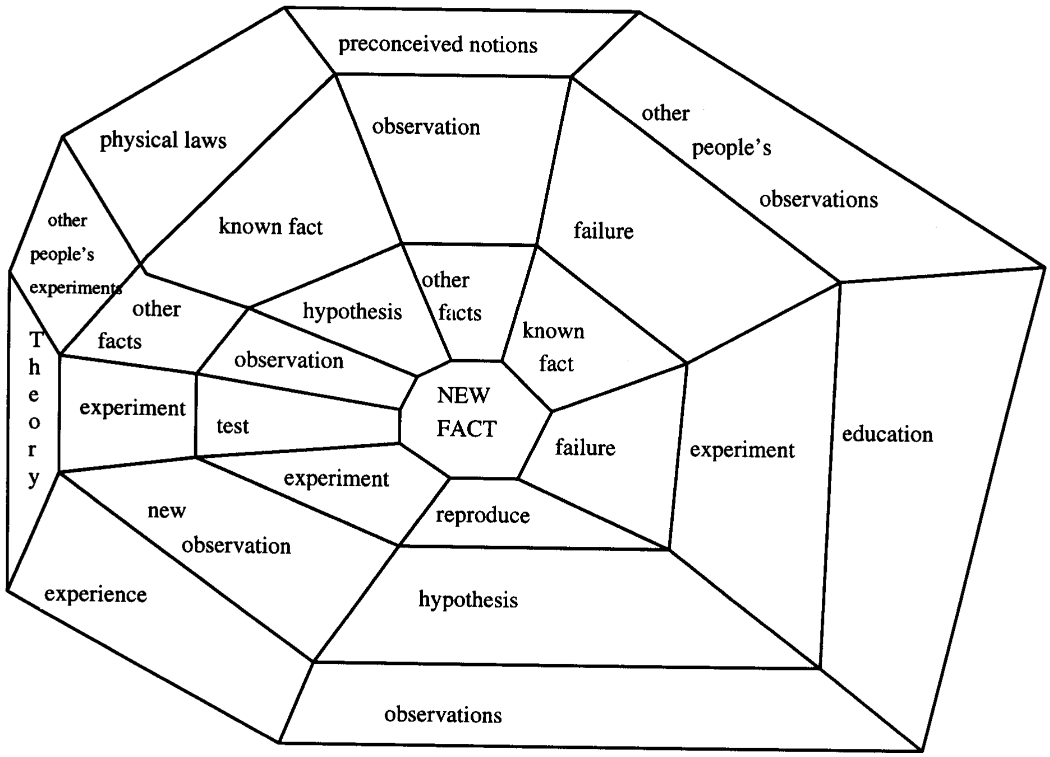

FIGURE 2. A COMPLEX WEB OF OBSERVATIONS, EXPERIMENTS, FAILURES AND PRECONCEIVED NOTIONS IS USUALLY INVOLVED IN THE DISCOVERY OF A NEW FACT—IF A NEW FACT IS LEARNED AT ALL.

The short writing assignment ensures that all of the students are prepared to participate in class discussions that follow their attempts at transmutation. In discussing the experiments, collaborative small groups are effective. Much has been written about cooperative or collaborative learning and the mechanics of employing these strategies in the classroom [2, 3]. In our own classes, groups of four to six students work well. However, the total number of groups in the class should be small enough that the instructor has an opportunity to interact with each of the groups during the time they are working.

Some students find it difficult to begin the collaborative discussion and require some preparation or prodding. General questions to guide discussion are included in the student handout and it might be profitable to have students spend a few moments writing out their own answers to these questions before groups work begins. When visiting groups, questions from the instructor about rationale, methods employed, and

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observations made can help to start stalled discussion. Typical questions raised in our classes included the following:

> How do you know that something is alive?
>
> What could you measure that would tell you?
>
> How much water did you use to soak the wax?
>
> Do you think the amount matters?
>
> Did the wax drink up any of the water?
>
> How do you know?
>
> Is that a guess or a measurement?

As discussion abates, the groups should be encouraged to select the best method for opening the ingots and examining their insides as an exercise in experimental design. Among the issues to be addressed are: 1) the likelihood of finding something alive inside the wax, 2) whether the method used to open the ingot might also kill any life inside, 3) the speed of analysis, and 4) the sufficiency of examining just a sample of the ingot. If desired, a second student handout can be distributed to describe this activity more fully.

Having decided on a course of action, the groups can be allowed to open the wax ingots for a more thorough examination. When the students open the ingots and find seeds inside some, they will need to reconsider both their initial predictions and their experimental design. Following group discussion, the class can be reassembled to share results. The principle point to be emphasized by this wrap-up is the importance of a control experiment. Without controls, it is not possible to determine whether seeds appeared in the wax as a direct result of the experimental protocol or if their appearance occurred independent of the treatment. The outcome of this discussion should be agreement on how the experiment could be repeated to yield more scientifically satisfying results. Other important points may come up or can be introduced. Among these are reproducibility of experimental results, acceptance of scientific findings, and peer review. Issues related to public policy on science, research funding, and the relationship between science and business can also be included.

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The "transmutation" activity suggests a number of related, high-interest writing or research questions. Some suggestions for this type of follow-up are:

> Can lead really be turned into gold? What is the modern view of transmutation? To what extent does transmutation occur in nuclear reactions? Can any of the elements be "made" by transmutation?
>
> How does the amount of chemistry information available to you compare with what was available to the alchemists?
>
> How do you decide whether someone else's results are valid?
>
> How do you distinguish scientifically valid information from scientifically invalid information? (e.g., Are diet recommendations you read in a newspaper or magazine valid? How do you know?)
>
> Because the method the alchemists used to do their work was not the scientific method, we call their work pseudoscience. Identify other examples of pseudoscience in popular culture and tell why they do not qualify as science.
>
> Learn more about the alchemists. What were their scientific accomplishments? Are any of them known by name?
>
> Is pseudoscience just another way of saying non-Western science?

Preparation of Wax Ingots

Wax ingots can be prepared from sealing wax, candle wax, or paraffin. To prepare the ingots, melt the wax over hot water. To add color, which helps to disguise the enclosed seeds, a few crayons can be melted in the wax. When the wax is melted it can be poured into molds to harden. Disposable, 10-mL polyethylene beakers are good for this purpose, but small cupcake papers or candy molds also work. To enclose seeds, pour a shallow layer of wax into each of the forms. When this first layer has nearly hardened, press one or a few seeds into the wax surface in selected forms. Then pour a second layer of wax over the top of the seeds. Seeds that work well for this purpose are lentils, popcorn, wheat, and kidney beans. We put seeds into approximately 75% of the ingots to insure that some "failures" are recorded.

To add another variable to the activity, ingots of different colors can be used in the same class. These characteristics of the ingots, not essential to this experiment, are "red herrings" that may lead to spurious conclusions by creative students. For

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example: Red wax is more efficient at generating life than green wax or yellow wax always produces popcorn while brown wax produces lentils.

Some Useful Background on Alchemy and Transmutation [4]

Transmutation of Wax offers an opportunity to introduce the history of science and multicultural issues to the class [5, 6]. For more than fifteen centuries, nearly ten times longer than modern chemistry has existed, alchemy was the very pinnacle of the physical sciences. *Khemeia* (the origin of the English words *chemistry* and *alchemy*) is a word of unknown origin describing a combination of science, art, and religion practiced by the ancient Egyptians [7]. Later, the Greeks refined *khemeia*, discarding its mystical elements. The *Four Element Theory*, originally proposed by Empedocles (ca. 490–430 B.C.), stated that all matter was composed of the four elements: fire, air, water, and earth in varying proportions. Bolos of Medes (ca. 200 B.C.) used the four element theory to reason that one substance (e.g., lead) could be changed into another (e.g., gold) by adjusting the proportions of its component elements. Thus, transmutation was born. Bolos spent his life examining this problem and spent a great deal of time trying to make gold.

The concept of transmutation did not seem unusual to the ancients. The powdery red pigment cinnabar (HgS) was prepared by heating a shiny liquid metal with yellow sulfur [8]. Blue rocks could be heated to form copper metal. Brown rocks and charcoal could be heated to form iron. The technology for producing Cu, Fe, Pb, and Sn metals was well-developed by the time Bolos of Medes began his investigations. In his writings, Bolos described a process for making gold. Today it is thought his process probably combined zinc ore with copper—producing brass rather than gold. The Egyptian–Greek era of *khemeia* ended with the spread of Christianity. The library and museums at Alexandria, which held most written accounts of the science, were destroyed in Christian-led riots in 400 A.D.

In the Arab world, *al-kimiya* (alchemy) was resurrected after Egypt was conquered by the armies of Islam in 641 A.D. The study of *al-kimiya* reached its zenith between 760 and 815 A.D. Jabir ibn-Hayyan, who studied the transmutation of metals, introduced the concept of an *al-iksir* (elixir) to facilitate the transformation. Alchemy was discovered by the Europeans after the Crusades when the French monk Gerbert (later Pope Sylvester II) translated Arabic texts on the subject.

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At various points in history, alchemy was outlawed by the Christians, Arabs, and Europeans, even though the alchemists made many advances in both chemical and medical sciences. Alchemy was considered to be consorting with the devil, witchcraft, or pagan mysticism. The fear that an alchemist would succeed in creating gold was probably the major reason that secular governments outlawed the practice, but this was rarely the official reason. In spite of persecution, the study and practice of alchemy continued; its practitioners were always fascinated by the possibility of transmutation of base metals into gold. This idea persisted, even as alchemy became chemistry. Robert Boyle, considered by many to be the first chemist, is said to have believed in transmutation [9].

In the 13th century, the preparation of nitric acid allowed lead to be analyzed prior to its use in transmutation experiments. This analysis demonstrated that gold is a common impurity in lead, convincing many that any positive results from transmutation experiments had always been false. Some alchemists, however, took this information to indicate that lead naturally turns into gold as it ages. These two opposing opinions were generated from the same data—a reminder that the pathway of scientific progress is seldom straight and is often bumpy. The unrecognized inclusion of the desired product as a contaminant in the starting material is analogous to our *transmutation of wax* activity.

Alchemy has intrigued people for nearly 21 centuries, despite the fact that no conclusive proof of transmutation was ever established. Many science professionals and students, as well as the general public, have a long-standing romantic relationship with alchemy. Evidence of alchemy's ability to captivate is seen in popular culture and art. Consider, for example Mickey Mouse's alchemical adventure in Walt Disney's *Fantasia* and the Nobel Prize-winning novel *O Alquimista* by Paulo Coelho [10]. Today, the alchemists and their science are often scorned, but they are improperly maligned. Collectively, these fools and mystics expanded the theory of the elements proposed by the Greeks, they identified at least 10 of the 92 naturally occurring elements (11%), and developed the first medicinal herbal remedies known to Europeans.

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