A Bright Spark: Open Teaching of Science Using Faraday's Lectures on Candles

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> There is no better, there is no more open door by which you can enter into the study of natural philosophy than by considering the physical phenomena of a candle.
> —Michael Faraday

Science today abounds with exciting new discoveries, especially in the fields of biotechnology, genetics, and space exploration, many of which can be used to generate an interest in science among students. However, it is often the case that the most simple and traditional of science phenomena are the most effective at teaching students to use science process skills and gain scientific content knowledge. Michael Faraday chose one such simple phenomenon, the chemical history of a candle as the theme for a series of lectures he gave at the Royal Society in 1860 *(1)*. These lectures have become a classic example of how scientific principles and ideas can be deduced through the use of simple practical work and reasoning. The simple experiments contained within these lectures provide an excellent and accessible introduction to the world of chemistry for students.

Science didactics emphasizes the use of student-centered, open-teaching techniques, where students decide for themselves what the results of experiments mean. A teacher in a student-centered and open classroom uses probing questioning to prompt students to try different things and to think up explanations for the things they are seeing themselves. An open classroom is one where students conduct experiments and then develop explanations for the phenomena they see, instead of being given an explanation by the teacher that they then have to "prove" is right through experimentation. The teacher's role in an open classroom is to guide and support students as they develop their own ideas. Faraday's lectures and the experiments he demonstrated are especially suitable for teaching in these ways because of their simplicity and because they can be used to prompt students to make reasoned conclusions. Another advantage of these experiments is that many are hands-on; students can do many of the experiments and not simply watch as the teacher performs them at the front of the class.

The German science educator Martin Wagenschein, a specialist in open and student-centered teaching techniques, first identified the possible potential of Faraday's lectures on candles for use in such an environment *(2)*. Theophel took this idea up and developed a lesson plan about burning in candles suitable for teaching over some weeks *(3)*. We have further adapted the lectures and experiments presented by Faraday to develop a new and original lesson about candle burning that further emphasizes ideas of open teaching and student-centered learning and inquiry.

The experiments given here are suitable for students of a variety of ages; we have used them with success with both primary schoolchildren and with university students. Teachers may have concerns about the safety of letting younger students conduct some of the experiments mentioned, such as those involving placing glass slides or powders into or above a flame. These experiments can instead be conducted by the teacher at the front of the class to ensure student safety. Although the teacher demonstrates these experiments, students can still be asked to explain what they think is happening and why.

Although the experiments can be used with students of all ages, lessons using these experiments should be tailored to the abilities of the students. We have used the same experiments with different age ranges of students. In our experience younger students are able to make similar conclusions as older students, but simply need more time and prompting. With university students the whole process from beginning with the observation of a candle flame to elucidating what exactly is happening during burning can be fitted into a single hour lesson. University students quickly build long lists of observations and are quick to provide ideas for what they believe is occurring. When the same experiments were conducted with primary school students the process took over three lessons and ran over two weeks.

How Do Candles Work?

The lesson began with the teacher posing a deceptively simple question, "How do candles work?" Although this question seemed initially easy to answer, with thought moststudents realized that actually they do not know how and why candles burn. This was the problem the students had to answer. As scientific study often begins with the making of observations, the teacher prompted the class to light the candles so that they can be "set to work in the performance of their proper functions" as Faraday said. The students were asked to observe the candle flames and then to draw and describe them in their notebooks.

Once the students finished this task the teacher asked the students to share their ideas and thoughts in a class discussion, starting off with the question, "What does a candle flame look like?" The teacher asked students to draw a diagram of a candle flame on the blackboard and then to add notes or changes as they suggested or found new features. The teacher continually asked questions to prompt students to make new observations and find new details they had previously missed or not thought about: "What color is the flame?" "What differences, if any, exist in its color?" "What shape is the flame?" "What is the outline of the flame like?" "What about the wick, what does it look like?" "What is the wax like?" Faraday spent considerable time describing and comparing different types of candles in his first lecture; in our version the students make these observations. As in Faraday's lecture the complexity of the candle flame soon becomes apparent. At first, describing a candle flame seemed relatively straightforward, but with increased observation the finer details became apparent. Typically, once they got the idea, students found dozens of properties of a burning candle. "Who would have thought there was so much to see in a candle?" was a common exclamation from students.

When the diagram was nearing completion the teacher asked, "What happens to the candle over time?" Some of the students answered that they thought the candle would get shorter, in other words, the candle would disappear. Faraday called this disappearance of a candle as it was burnt "a very curious circumstance". And indeed it is. The teacher followed up this idea to see whether the students understood what happened when candles burnt: "Why do you think the candle disappears?" "What do you think happens to the candle?" The students answered that the wax gets "used up" as the candle is burnt. This provided a good starting point for practical experimentation.

The Theory of Burning

Combustion or burning is a chemical reaction in which a fuel reacts with a gas, usually oxygen, and results in the production of energy in the form of heat and light and of matter in the form of carbon dioxide and water. During combustion the compounds that make up the fuel react with the oxygen and each element of the compounds become oxidized. Combustion can be summarized in the form of a word equation as

$$\text{Fuel} + \text{Oxygen} \rightarrow \text{Heat} + \text{Water} + \text{Carbon Dioxide}$$

The fuel in a candle is the candle wax. Nowadays candle wax is not made from real wax, but is made from kerosene, otherwise known as paraffin (C_nH_{2n+2}), that is obtained from oil:

$$C_nH_{2n+2} + O_2 \rightarrow CO_2 + H_2O$$

This is a simple explanation of what happens when something burns. Standard chemistry textbooks provide more detailed explanations. In this lesson the teacher used careful questioning and simple experiences to help students to work this out. It was easy to get students to do this if they were prompted to find out what things a candle produces when it burns, and what things it requires to burn. Instead of simply telling the students what burning is, a teacher in an open classroom asks questions that helps students make important conceptual links that draw on real experience.

What Does a Candle Produce When It Is Burning?

Students were asked whether they could name some of the things candles produced as they burned. The two most obvious products a candle produces are heat and light. If students are unable to name these two products, they can be prompted to find them by being asked what we use candles for or what happens when you put your hand too close to the candle flame. However a burning candle also produces a number of other products apart from these two and these are more difficult to notice. These products only become apparent through experimentation.

Students were next asked, "So far, you've mentioned that light and heat are emitted from a burning candle. However could the candle be producing something else which you could not see so easily? What do you think?" Students quickly came up with the idea that candles produce a gas, and then were questioned as to how they could collect some of this gas and show what it was. Students can come up with ingenious ways of collecting gases and should be allowed to try some of them if they are safe and there is time. Otherwise they should be shown how to collect gases by placing a beaker over a candle and then placing a glass plate over it. Students often know that different gases react in different ways to flames. For example hydrogen produces a loud bang when it is introduced to a flame, while oxygen makes a flame burn more vigorously. Students can try these tests with the gas they collect from a candle flames to eliminate them as products of burning.

Students were then asked to siphon the gas coming from a candle into an enclosed beaker of limewater using an array of tubes. Ordinary household candles were used. The gas from the candle caused the limewater to become a cloudy milky color. Some university students knew that this was because the gas from the candle contained carbon dioxide and this experiment shows that the candle produces carbon dioxide as it burns. Younger students who do not know this can be asked why they think the limewater became cloudy, and when they realize that there must be something coming from the candle that makes the limewater cloudy they can be told the limewater "collects" carbon dioxide.

Another way of helping younger students understand that the candle emits carbon dioxide is to have them exhale into limewater until it goes cloudy. Many younger students know that their exhaled breath contains carbon dioxide, and when they see that the burning candle makes limewater cloudy in the same way as their breath, they will understand that candles also emit carbon dioxide.

Another product produced when a candle burns is water. However students probably will not raise this as a possible product! Instead the teacher will have to introduce this idea to the students, maybe by saying, "I want to show you something else that Faraday noticed when he studied burning candles." Then this can be demonstrated to students by using a metal block that has been in the freezer for some time and holding it over a candle flame so that water droplets collect on it. The students can try for themselves. Now the students have found two of the main products of burning: water and carbon dioxide. These can be placed on the blackboard as being the products of a reaction.

Some students may also mention that soot is given off by a burning candle. Despite this not actually being a product of the burning reaction it is best to place it on the blackboard, but with a question mark next to it and say you want to talk about it later after the students have done some experiments. By then they should have found out that soot is incompletely burned carbon and not a product of the burning process.

Students may suggest other things a candle gives off as it burns. Where appropriate allow students to test to see whether the things they suggest are produced.

What Does a Candle Need If It Is To Keep Burning?

We next wanted the students to work out what actually gets used when the candle is burning. The most obvious thing needed is a fuel, in other words, the candle wax. But how can we show students that this is what is burnt in a candle flame?

Often when asked how a candle burns, some students may say that what really burns in a candle is the wick, and the wax is simply there to slow the wick from burning down too quickly. To get around this misconception we used a small oil lamp, and asked the students what they think is burning in it: "Is it the wick, or is it the oil at the bottom of the lamp? Does the lamp work without oil? Why not?" Hopefully the students will realize that the fuel of the lamp is the oil, and from here you can ask the students what they think the fuel of the candle is, "Is it really the wick or is it something else?"

Students can be prompted further by being asked to look at the incomplete formula of burning on the board. Students were asked to think about the things that the candle emits as it burns, the ones of the "out" side of the equation. If something comes out, then it has to be put in somewhere. What else is needed by the candle? Where could this come from? Hopefully students will be able to work out that carbon and hydrogen are also needed for a candle to burn and that these must be what the candle wax is made up of.

We now wanted the students to see that a candle flame needs oxygen to burn. We went back to the formula for burning we were developing on the board. We had shown that a candle produces CO_2 when it burns, even though we can not see it, did the students think a candle would need something that they could not see, like a gas, to burn? How could they find out?

The teacher suggested an experiment. Students placed a beaker over the candle flame so that it was completely separated from the outside air. After a few seconds the flame went out, thus showing that the candle needed some gas to burn. When the flame was enclosed by a beaker it used up all this available gas and then went out. But what gas could it be that the candle needs? Some students may already know. But if not, one of Faraday's experiments can be used to show which gas is needed. Faraday showed his students the effects of putting flames into beakers of pure oxygen and beakers containing pure nitrogen. Faraday showed that oxygen causes the flame to burn much more vigorously, while in the nitrogen the flame is extinguished.

Burning in the Candle

Now the students have looked at the theory of burning and worked out what a flame needs to burn and what it emits as it burns. But how exactly does a candle flame burn in practice? It is one thing making up a formula for how a candle burns but we also need to see how the real thing works. How does the candle burn the wax? Why and how does the candle produce light?

What Actually Burns in a Candle Flame?

The students were instructed to blow the candle out and asked what they saw. Often the students would see a plume of white smoke emerging from the wick. This rose upwards and gradually faded away. When the oil lamp was blown out no smoke emerged. The teacher then asked, "What do you think this smoke is? What does a candle have that the oil lamp does not have?" Some students believed this was some of the wax from the candle that had been turned into a gas. The students were then instructed to try to relight the candle simply by placing a lighted splint into the white plume of smoke, but they had to do this quickly before the white smoked dissipated too much. Some students tried seeing who could light the white smoke furthest from the candle. This experiment showed that the wax is the "fuel" for the candle and is what burns in the candle flame.

In another experiment students were instructed to try to catch the gas coming from a candle in a glass tube and then to light the gas at the end of the tube or to place a sheet of metal gauze over the candle flame and then to light the gas emerging from the top of the gauze. Students were asked, "What did these experiments show?" and "What was needed for the flame to burn?" The students answered that if what burned in a candle was the wax vapor, then the reason a flame could be lit from the gas collected from a candle was because it contained wax vapor and that this could be lighted. This experiment confirmed what the students had learnt previously, that the candle wax contains carbon and hydrogen and that these are needed for burning to occur. If the inputs needed for burning are not present no burning can take place.

How Does the Wax Get to the Flame?

Next the students were asked to observe their candles and to say what happened to the wax at the top of the candle: "What was it like? What did it do?" As Faraday they saw that the wax at the candle tip melts into a liquid. However there is a problem, if this liquid is the fuel for the flame how does the flame get enough wax to keep burning? The flame is at the end of the wick, but the wax is part of the candle away from the flame. How can the wax get to the flame?

The students were asked to conduct an experiment to find out what happened when a piece of chalk was placed upended in a beaker with a small quantity of ink at the bottom. After some time the ink begins to be drawn up the chalk. The chalk acts like a sponge absorbing the ink and pulling it upwards. Students were now asked to make a reasoned guess as to how they thought the candle flame got its wax using the evidence they had seen in this experiment. The melted wax at the top of the candle moves up the wick of the candle to the flame where it is then burnt, or as Faraday explained it by "capillary attraction"! There are a number of good examples of this phenomenon. Faraday showed an example of a blue salt solution moving up a column of salt. He also gave the analogy of a hand towel left dangling from a basin of water, which soaked up water and then dripped it onto the floor.

Why Do Candle Flames Burn Brightly?

The next question that was posed was "Why does a candle flame burn brightly?" The teacher placed a block of magnesium in a candle flame (older students can do this themselves but should wear goggles and work carefully, but younger students should have the experiment demonstrated to them by the teacher) and asked students to describe what happened. The teacher should emphasize that the magnesium acts in just the same way as the particles of carbon found in the candle, but magnesium is used simply because it is easier to see what happens when it is placed in a flame. When the magnesium was placed in the candle flame it produced an intense bright flame. This experiment can be conducted with various other substances such as iron fillings or copper powder. Faraday performed this demonstration with gunpowder mixed with iron fillings, but cautioned his students to take care if they repeated the experiment otherwise "much mischief will be done". A point that modern-day students often appreciate. With the gunpowder Faraday showed that the two different components, the iron fillings and the gunpowder, burnt differently.

The point of this experiment is to show that when a solid is burnt it becomes brightly luminous. In the same way that magnesium or iron fillings become brightly illuminated when placed in a flame, so do particles of carbon. In a candle flame the particles of carbon, which are released from the candle wax, become extremely hot and emit a strong brightness. These carbon particles are the source of the light seen in the candle flame.

The students were asked to place a slide some distance over the flame using tongs. After a few seconds the slides become blackened with a ring of soot. Why is this? What did the students think? If the students have realized that the candle emits carbon as it burns, maybe some will realize that not all the carbon will be burnt and some will escape as soot. If some of the carbon from the wax is incompletely combusted it will leave the candle as smoke and soot. If the students do not realize this then you can prompt them by asking what would happen if the flame were "inefficient" and did not burn well. This experiment can also be done by holding a small piece of card over the flame for a short period of time.

Where Does the Candle Burn Hottest?

The teacher posed the following question, "Where does the candle flame burn hottest?" One student answered that the center of the flame must be hottest, because the outside of the flame would be cooled by the air around it. This seemed a sensible answer, but how could the students find out whether this really was the case? The students did not have many ideas of how to do this, the main one being to place a thermometer into different parts of the flame. In the end we suggested an idea of how they could find out.

The students were asked to place a clean slide into the candle flame at various heights for a few seconds (again using tongs as the slide soon becomes very hot) and then to describe what they saw. When the slide is held over the candle flame dark black smoke collects on the slide as they saw in the experiment above. Faraday remarked that servants could use candle smoke to write their names on ceilings if the candle was held high enough. When a slide is held high over the candle flame smoke collects all over the slide in no discernible pattern. However, when the slide is held much closer to the flame, in fact actually in the flame, a distinct ring of black smoke is produced with the center of the ring remaining clear of smoke.

No charcoal smoke comes from the center of the flame, why is this? One students answer was that the center of the candle flame is probably where it is hottest, and all the wax is burnt away meaning that there no charcoal is produced there. However at the outer sides of the candle the flame is probably not as hot and the wax is not completely burnt and the charcoal pieces are incompletely burnt pieces of wax.

This was a nice explanation, but the teacher suggested another experiment the students could try to confirm it. If a wooden splint is placed horizontally for only a split second into a candle flame and then removed you can see which parts of the flame are hottest because these parts singe the wood black and the cooler parts of the flame do not do this. The students tried this experiment and found that a splint placed in the candle flame singed at the outer parts of the flame, but in the center it remained unsigned. This showed that the center of the flame was actually cooler than the outside parts. But how could this be? The students could not understand why this should be the case as there should be more wax in the flame center so it should burn better?

Students were asked to think about where oxygen was when the candle burned, and why this would mean the center of the flame burnt cooler than the outer parts. It did not take long for some of the students to catch on. The outer parts of the flame have access to ample oxygen because it is surrounded by air. The outer parts of the flame can use the oxygen in the air to burn to a very high temperature. The center of the flame on the other hand has access to very little oxygen, because the outer flame surrounds it and this uses all the oxygen up. Although the inner flame has lots of wax vapor that it could burn, it cannot do so because of lack of oxygen. The wax vapor therefore moves to the outer parts of the candle where it is burnt. This can be shown to be true by placing a slide low over a candle flame, this effectively reduces the quantity of oxygen the flame can use and the outer part of the flame shrinks, the outer flame forms a circle under the slide where it can still obtain enough oxygen.

Conclusion

Rather than being seen simply as an object, a burning candle should be considered as being a process. The wax in solid form in the candle is melted by the flame heat and moves by capillary action up the candlewick and is burnt in the flame. When candles burn, there is a chemical reaction between oxygen in the air and the heated wax vapor in which energy in the form of heat and light and carbon dioxide and water are produced. The experiments given here can be used to help students find this process for themselves. With good questioning and prompting from the teacher students can be forced to develop explanations for the phenomena they see without simply be given the explanations by the teacher.

[W]Supplemental Material

A summary of the different experiments is available in this issue of *JCE Online.*

Literature Cited

1. Faraday, M. *The Chemical History of a Candle;* The Royal Institution Lectures: London, United Kingdom, 1860.
2. Wagenschein, M. *Die pädagogische dimension der physik;* Schulbuchverlage Westermann: Braunschweig, Germany, 1962.
3. Theophel, E. Alle im Weltall wirkenden Gesetze. In *Lehrkunst-Lehrbuch der Didaktik;* Berg, Hans Christoph, Schulze, Theodor, Eds.; Hermann Luchterhand Verlag: Berlin, Germany, 1995.