

# Shining a Light on Candles

By Max G. Levy

**G**lancing up at a 700-person crowd in December 1860, Michael Faraday, a renowned English scientist, asserted in a lecture that the best example of nature's beauty is the humble candle.

"There is no better, there is no more open door by which you can enter into the study of science than by considering the physical phenomena of a candle," he said.

Coming from Faraday, whose sophisticated research led to society-transforming innovations in electric motors, transformers, and generators, candles might seem like an odd choice for a lecture topic. The opposite of innovative, they have been around for millennia and have just three basic ingredients—fat, fiber, and fire.

Historical records show that ancient Egyptians used an early form of candles 5,000 years ago, and many civilizations, including those in China and India, invented and advanced this basic device independently, using different materials. People have burned candles with animal fat, wax from whale heads, and beeswax. The Romans are credited with adding a papyrus wick to the equation more than 2,000 years ago.

But on to Faraday's point. Examining the burning of candles, as ancient as they are, still illuminates to this day!

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## WHAT IS WAX?

Waxes are organic substances that are generally solid though malleable at room temperature. They come from different sources, including plants, animals, and petroleum. Some waxes, such as beeswax, are naturally solid at room temperature. Others, such as waxes derived from vegetable oils, need to be hydrogenated to become waxy. Hydrogenation is a reaction between molecular hydrogen ( $H_2$ ) and another compound. In the case of vegetable oils, hydrogenation reduces double and triple bonds in hydrocarbons.

**Stearic acid ( $C_{18}H_{36}O_2$ )**  
A primary component in soy wax



Soy Wax

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**Docosane ( $C_{22}H_{46}$ )**  
A component in paraffin wax, which comes from petroleum



Petroleum

SHUTTERSTOCK

## WHAT MAKES A FLAME

In the late 17th and early 18th centuries, scientists attributed combustion to a special substance called phlogiston, which they believed to be intrinsic to any matter capable of burning. But by the late 18th century, scientists elucidated the science behind the flame.

With a series of experiments starting in 1772, French scientist Antoine Lavoisier showed that phosphorus and sulfur gain weight after burning. This observation and additional findings convinced chemists that combustion is a reaction between a material and a component of air that had been newly discovered: oxygen.

Lavoisier coined the term **oxidation** to describe oxygen's role in combustion, during which it snatches other atoms' electrons. Later, the term came to refer more generally to any reaction in which electrons are lost.

For organic molecules such as those in wax, burning—or combust—involves reactions with oxygen, which produce a lot of heat. Here's why: Breaking the carbon-carbon and carbon-hydrogen bonds in the wax consumes energy. But forming the stronger carbon-oxygen and hydrogen-oxygen bonds in the carbon dioxide and water molecules that are released generates more energy than is consumed. This release of energy helps continue the reaction by breaking more bonds in the molten wax. So, as long as enough oxygen and fuel exist nearby, the wax keeps burning.

## WHAT'S ACTUALLY BURNING

If you light a candle, or observe one burning, you might assume that the wick is the part of the candle that's burning. After all, to light it, you hold a match or lighter to the wick to start a flame.

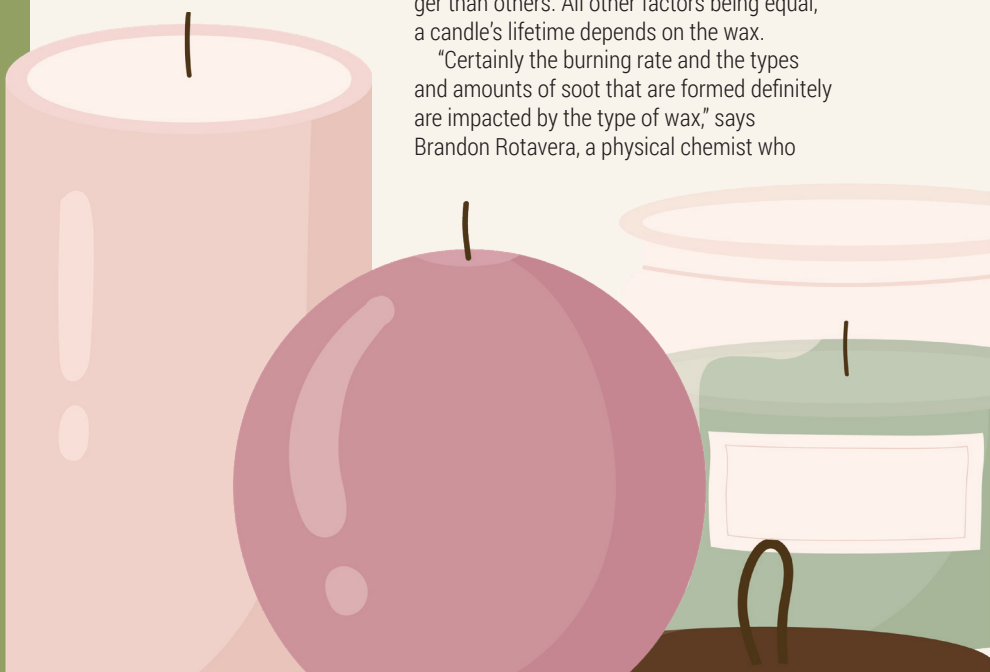
But breaking down the process into more detailed steps shows it's not the wick that keeps the flame going. Here's what happens: Solid wax blankets the wick on a new candle—so, when you hold a lit match to the wick, the heat from the burning match melts away the wax coating. Heat from the match also melts the wax at the top of the candle. This liquid wax is then drawn up into the wick via **capillary action**.

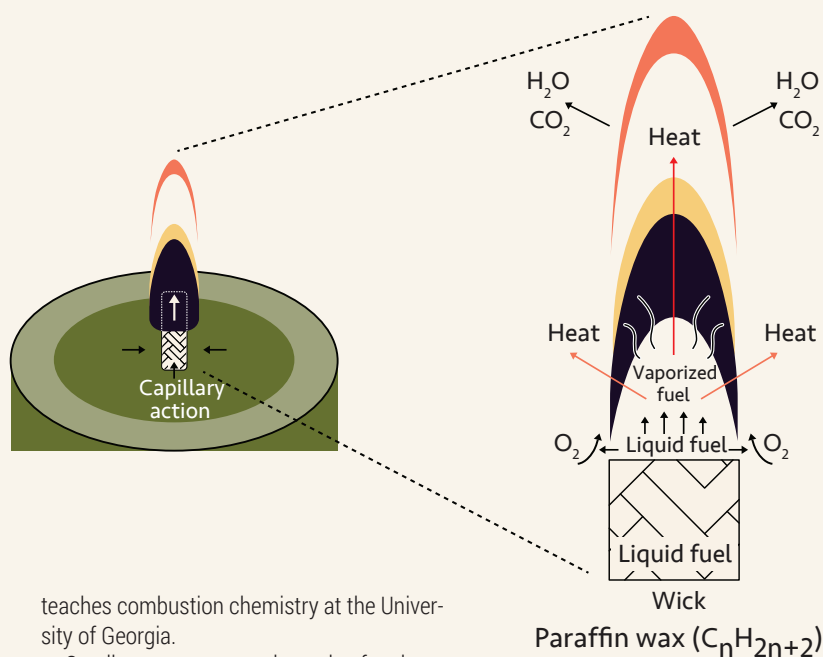
Capillary action refers to a liquid's flow upward in a narrow space without help from external forces. This seemingly gravity-defying movement occurs when adhesive forces that attract a liquid to surrounding "walls" are stronger than the cohesive forces that hold the liquid's molecules together. In the case of a candle, the walls are the braided wick surfaces. The adhesive forces between the melted wax and the wick are stronger than the intermolecular forces between wax molecules. This pulls the wax upward.

When the liquid wax reaches the flame, the heat causes the wax to vaporize. And it's the gaseous form that actually keeps the candle lit.

If you're a fan of candles, you might have noticed that some seem to last longer than others. All other factors being equal, a candle's lifetime depends on the wax.

"Certainly the burning rate and the types and amounts of soot that are formed definitely are impacted by the type of wax," says Brandon Rotavera, a physical chemist who





teaches combustion chemistry at the University of Georgia.

Candle waxes are mostly made of carbon and hydrogen. You can glean a lot about wax behavior from their chemical formulas.

A long carbon chain with double bonds and carbon rings will burn at lower temperatures and emit more soot than a **saturated hydrocarbon**, which only has single bonds between carbon atoms, Rotavera says.

**Unsaturated hydrocarbons** have one or more double or triple covalent carbon-carbon bonds, and are harder to burn.

Plant-derived soy or palm waxes can burn slowly or quickly depending on their composition. Stearic acid ( $C_{18}H_{36}O_2$ ), for example, is a primary component in soy wax. Hydrogen bonding occurs between the double-bonded oxygen of one stearic acid molecule and the hydrogen of the hydroxide group of another stearic acid molecule. This stabilizes the wax's liquid and solid forms—making it harder to vaporize.

Plant-derived waxes are less likely to contain impurities such as benzene, so many researchers regard them as cleaner burning than petroleum waxes.

Paraffin wax ( $C_nH_{2n+2}$ ), the most common candle fuel, is a mixture of straight-chain hydrocarbons at least 20 carbon atoms in length. It's a petroleum byproduct, which makes it relatively easy to source and less expensive than alternatives such as beeswax. It also tends to burn faster than other waxes, making it better for emitting fragrance. Candles are scented by adding fragrance molecules to the wax, so when a candle burns quickly, it releases the fragrance molecules quickly.

Solid wax undergoes physical and chemical transformations whenever a candle burns. Since each transition depends on wax properties, such as carbon-chain length and molecular structure, candles underscore how important it is to choose the right fuel.

## DESIGNING THE BEST WICK

Wicks submerged in that wax are more than just string; they help regulate how quickly the wax evaporates and burns. Only the wax high in the wick gets hot enough to vaporize and ignite, but the wick also conducts heat downward, melting solid wax into a liquid reservoir that replenishes the wick. After gaseous wax molecules burn off, producing a blue flame, more wax molecules replace them, flowing up the wick through capillary action like a conveyor belt.

Soaking the wick in a fire-retardant chemical keeps it from burning too fast. If it burns too quickly, the tip would drown in molten wax. Treating the wick involves chemicals, such as borax (sodium borate), that bind to a wick's cellulose fibers and help form a protective layer of char. Wicks must typically be braided tightly to control fuel burning. A loosely braided wick draws up fuel well but leaves more surface area exposed to oxygen.

"[In these cases,] you've got more of the fuel exposed to the burning environment," Rotavera says. "They've got more localized hot spots, more localized points of ignition."

In slow-burning beeswax candles, unburned wax, pigments, and fragrances can clog up the capillary flow in thin wicks. But robust square wicks can prevent clogging by doing a better job absorbing melted beeswax. For all wicks, the mission is the same: soak up fuel at the right rate to burn slowly and evenly.

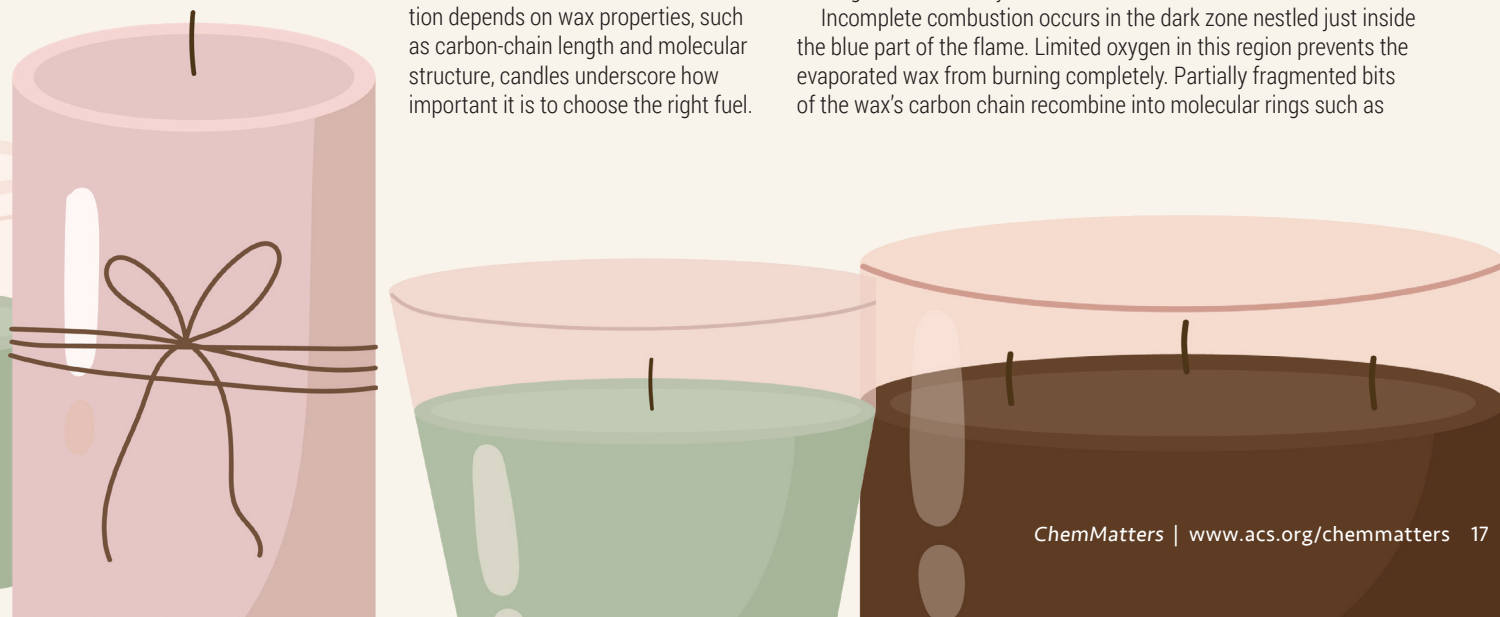
## ANATOMY OF A CANDLE FLAME

Regardless of which wax or wick a candle contains, they all look quite similar when burning: a multicolored flame in a distinct teardrop shape. That characteristic shape arises from convection.

The burning candle releases a large amount of energy in the form of heat. This heat, in turn, warms the molecules and atoms in the air. As the temperature of the air increases, the volume of the air increases, according to Charles's Law. As the air expands, its density decreases, causing it to rise. Cooler, denser air rushes in from below, creating an upward current that contours the teardrop flame.

Of the flame's regions, the zone at its base is blue—a region where evaporated wax combusts completely. Complete combustion means that all the carbon and hydrogen will react with oxygen to form  $CO_2$  and  $H_2O$ . After heat snaps carbon bonds, C–H radicals get excited and emit blue light, Rotavera says.

Incomplete combustion occurs in the dark zone nestled just inside the blue part of the flame. Limited oxygen in this region prevents the evaporated wax from burning completely. Partially fragmented bits of the wax's carbon chain recombine into molecular rings such as

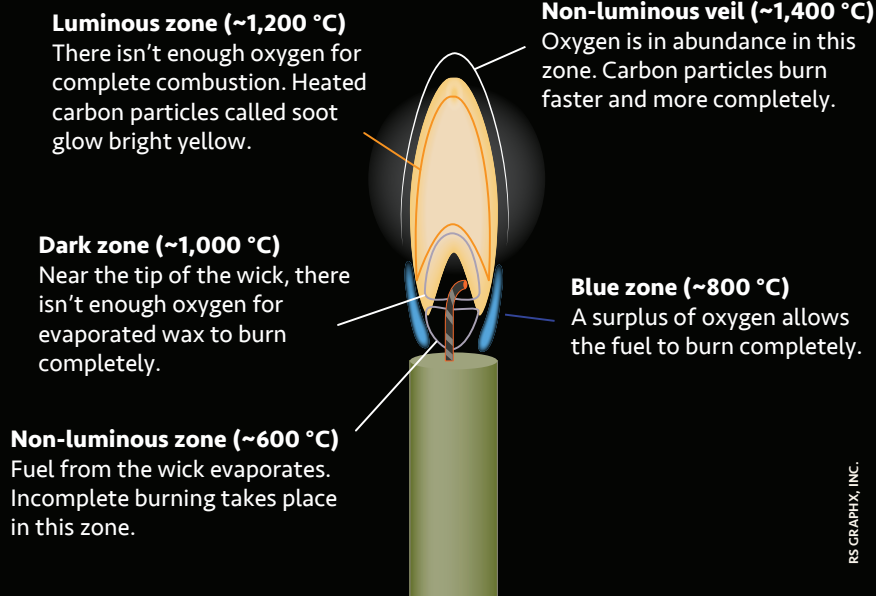




### FLAMES IN SPACE

An experiment on the International Space Station showed that in space, flames don't undergo the same convection as they do on Earth, because low-density air doesn't rise without gravity. This lack of buoyant convection creates a spherical flame. In microgravity, spherical flames are bluer. Scientists believe that without convection, enough heat stays well distributed around the burning molecules. This stagnant blanket of heat leads to more complete combustion and less incandescence—a dimmer but more efficient flame.

## ANATOMY OF A FLAME



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benzene. The rings multiply around each other.

"Multi-ring systems grow and grow and grow until they get large," Rotavera says. "And those aggregate into a particle."

These dark, carbon-rich particles called soot exit the dark region of the flame just above the wick without burning. The flame's heat then makes the soot glow bright yellow in a physical process called incandescence.

### LEARNING FROM CANDLES

Beyond improving upon their everyday uses and understanding the role they played throughout history, studying candle flames might help us improve other technologies.

"When I think about the candle, I think about these sporadic kinds of moments where there's a flickering of the flame or popping noise, or something like that," Rotavera says. Similar instabilities happen unpredictably in even the most cutting-edge engines. As the scientific community focuses on making the most-sustainable engines, weeding out inefficiencies is critical. "That really is something important to predict because engines need to operate routinely and consistently."

Another example of flame research that might be useful is NASA's experiments testing flames in microgravity. These studies are helping engineers design engines that burn fuel with less soot.

Regardless of the ultimate uses we find for candle chemistry, it's good to remember that it all started with curiosity.

"We come here to be philosophers," Faraday said. "I hope you will always remember that whenever a result happens, especially if it be new, you should say, 'What is the cause? Why does it occur?' and you will in the course of time find out the reason."

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