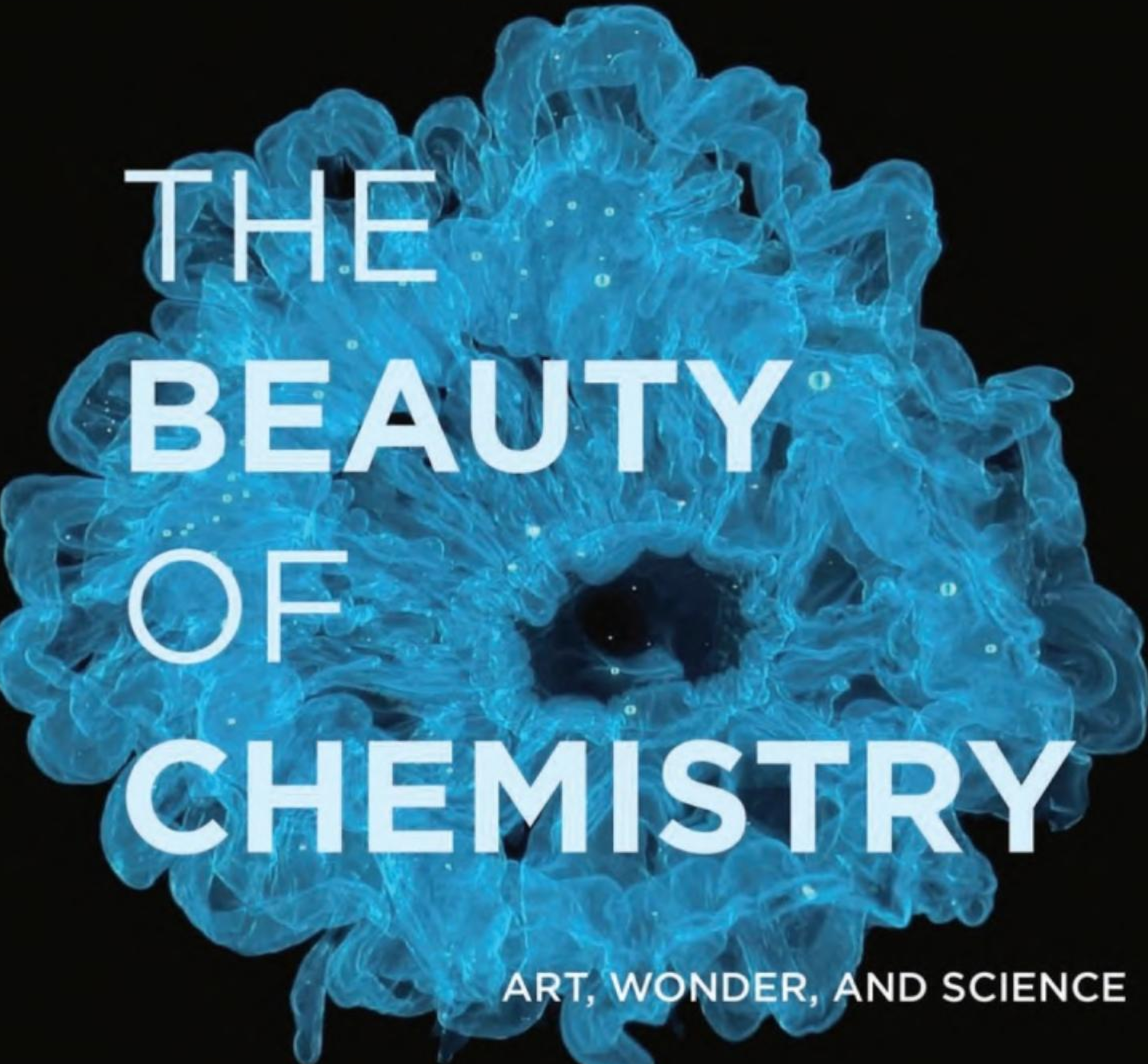

THE BEAUTY OF CHEMISTRY

ART, WONDER, AND SCIENCE

PHILIP BALL
photographs by Wenting Zhu and Yan Liang

ELEMENTAL: THE CHARISMA OF CHEMISTRY

Chemistry, more than any other science, is a confluence of the practical and the sublime. It's best known in the first of these guises: as the prosaic source of the substances all around us, by which our lives are increasingly shaped for better or worse. We are apt, like ungrateful children, to take for granted the dyes that clothe us in fashionable and flattering shades, the artificial scents that hide our own, the medicines that relieve our aches and ailments, the tiny slices of high-tech semiconducting alloys in our smartphones. We grumble (and so we should, although not at chemistry) about the pollutants in our air and water, the plastics clogging our rivers and seas. Chemistry gives us the fabrics of our existence: polyesters and polycarbonates, touchscreens and batteries, non-stick pans and non-drip paint. We depend on its bounty but fear its baneful influence: it is both problem and cure, nemesis and savior.

The chemical sublime is less familiar, but this book will introduce you to it. We will show some of the astonishing beauty that resides in chemical products and processes. This beauty too often passes unseen, or at least unacknowledged as chemical in nature. We can marvel at the delicacy of a snowflake, or the glory of a flower and its heady fragrance, while failing to realize that chemistry is at work here every bit as much as it is in oil refineries and pharmaceutical plants.

There doesn't seem to be a word for people who take delight in *stuff*, but there ought to be. We propose that they be called ousiophiles, from the Greek *ousia*, meaning essence or substance. Chemists are usually ousiophiles: they delight in tangible material, in texture and heft, in luster and pliancy. They want to touch and feel things, to smell and taste them. It's in this impulse that a love of chemistry resides; people who have it are often drawn to study the subject.

The Italian writer Primo Levi was undoubtedly an ousiophile. Levi wrote two particularly famous books, and one of them was *The Periodic Table*, a love letter to the primal substances, the *elements*, of chemistry. The book's title alludes to the iconic scheme used to arrange the chemical elements and which reveals the hidden order among them. Each chapter of Levi's book is named after a chemical element—argon, hydrogen, zinc, iron, potassium, and more—and makes its titular substance a character in a story, generally drawn from an episode in Levi's life. He revels in the materiality of these substances: chromium, mixed into an orange anti-rust paint in the factory outside Turin where Levi worked after the Second World War, or the "generous good nature of tin, Jove's metal." *The Periodic Table* brought a chemical sensibility to the notice of readers who might have remembered nothing from their school chemistry lessons, not even the blocky format of the periodic table itself.

Levi's other famous book is *If This Is a Man*, an account of the time he spent in the concentration camp at Auschwitz. There his knowledge of chemistry saved his life by making him eligible to work in the laboratory that served the Buna industrial plant, set up to make artificial rubber for the Nazi war effort. If it had not been for that assignment, it is unlikely Levi would have survived in Auschwitz during the harsh winter of 1944. Because he did, the world got to see this vital, harrowing, deeply humane account of atrocity.

Ordering the elements

To some chemists, the periodic table has almost the status of a catechism. Within its rows and columns of elemental symbols is encrypted much of what chemistry is about. It's not just that these elements are the building blocks of the subject, the varieties of atom from which all the physical world is constructed. The shape and topography of the table, gathering together elements with shared chemical properties, reflect the principles that govern atomic unions, dictating how elements may be combined to produce all the beauty and richness, the hazards and surprises, of the chemical world. To the initiated, the location of carbon (say) hints at its role in living things, while it is because the alkali metals come first in each row of the table that the chemist knows they will be highly reactive, dangerous to the touch. By the same token, by ending each row the inert gases such as xenon and argon are granted their lack of reactivity. Levi used them as metaphors for the character of the Jews of Turin from whom he was descended, alluding to their "attitude of dignified abstention."

The periodic table was internationally celebrated in 2019 to mark the 150th anniversary of its first appearance. (By coincidence this was also the centenary of Primo Levi's birth.) In 1869 an early version of the table, sketchy and full of gaps, was unveiled by the Siberian chemist Dmitri Mendeleev. He was by no means the first to recognize that the chemical elements can be grouped into families in which all the members show similar behavior. And if Mendeleev had not discerned the way these groups fit together, others would surely have done so around the same time. But Mendeleev was almost alone in trusting this deep structure enough to leave gaps where he figured new elements, as yet undiscovered, should exist. Those gaps were filled in due course, and Mendeleev's predictions about the properties of these missing elements were borne out.

The periodic table of the chemical elements doesn't self-evidently deserve the reverence that many chemists seem to feel for it. It's not a terribly elegant structure. With its rows of elements rising to turret-like peaks at either end and the long block of elements (called the transition metals) in the middle, the shape resembles a somewhat ungainly modernist housing development. Besides, chemists aren't even agreed today on exactly how the table should be drawn; there are still disputes about where some of the elements should be placed.

All the same, the recognition of this hidden order among the profusion of elements implied that there are deeper principles that determine their chemical properties. It took a further half-century after Mendeleev's publication to figure out what these principles are.

A key part of that puzzle was supplied in 1916 by the American chemist Gilbert Lewis, who argued that the chemical properties of the elements could be understood from the nature of the atoms of which they are composed. In the early years of the twentieth century, scientists discovered that atoms are not dense, featureless little balls of matter as had once been supposed, but have some internal structure composed from yet more fundamental particles. They have a very dense nucleus, which has a positive electrical charge and contains particles called protons (and also electrically neutral particles called neutrons, not discovered until 1932). Around the nucleus are arrayed much lighter particles called electrons, which have a charge equal in size but opposite in sign to that of the proton. Most of the atom is empty space; in one of the earliest pictures they were envisioned as tiny solar systems, with the nucleus as a kind of sun orbited by planetary electrons. This is too simplistic an image, but it was good enough to be useful for understanding how atoms of matter are constituted.

Discovering the internal structure of atoms was no small feat. A carbon atom (say) is just 0.17 millionths of a millimeter across, which is far too small to see inside with any microscope. It is not easy even to believe in objects so small; in the early twentieth century, some scientists (including Mendeleev) did not. But they do exist—we're now certain of that.

Lewis suggested that there is a "kernel" in each atom, made up of the nucleus plus some electrons, with a net positive charge equal to the number of the column in the periodic table in which it sits. In other words, elements in the first column (the alkali metals) have a kernel with a charge of +1, and so on. Around this kernel is a "shell" of as many electrons as are needed to balance out the charge. For the alkali metals, the shell has a single electron.

Lewis proposed that this outer shell can contain up to 8 electrons: this maximum number is found in the inert gases. This idea makes some sense of the fact that (if you ignore the wide block of transition metals in the periodic table) there are eight columns in each row: the so-called "main block" elements.

He proposed that the electrons can be thought of as sitting at the corners of a cube. Why a cube? That was simply a neat way to imagine the atom, since cubes have eight corners. Lewis didn't want to suggest that atoms literally have this shape. When atoms join together to form chemical bonds—linking them into groupings called *molecules*—they can then be imagined (again, not literally) as cubes sharing corners or edges. The electrons at the shared corners are then assigned to both atoms, and each pair of shared electrons makes a chemical bond.

Why should the outer shell of electrons involved in bonding have this eightfold capacity? Lewis had no explanation. Nor could he really explain why hydrogen and helium poke out at each end of the main blocks of the periodic table, with no elements in between them, nor why the transition metals interrupt the third and subsequent columns of the main block. These aspects of the table's structure became understood within a few years of Lewis's suggestion, once physicists worked out the fundamental rules governing the way electrons are arranged around an atomic nucleus. These rules emerge from the theory called quantum mechanics, which describes how very small particles like electrons and atoms behave. Quantum mechanics makes perfect sense of the blocky shape of the periodic table.

It's a source of great satisfaction to scientists when they are able to explain something com-plicated in terms of ideas that are simpler. The motions of the planets in the night sky, as seen from Earth, look perplexingly complex, even though there are regularities to them. But once you understand that the Earth is one of those planets too, traveling in near-circular (elliptical) orbits around the Sun, the pattern becomes clear and what previously seemed intricate and even a little awkward now takes on a certain elegance. It was the same for the elements: once we understood them in terms of the way electrons are organized around their constituent atoms, apparent complexity gave way to deep simplicity.

A sense of wonder

Many scientists find a genuine aesthetic pleasure in such abstract reasoning. They look at the periodic table of the elements, and they see beauty. You might share that response—or you might not. Maybe it takes a particular frame of mind to equate intellectual understanding with beauty.

You do not, however, need to have such a mind in order to appreciate the beauty of chemistry. We hope that this book will persuade you that chemistry unfolds with a beauty that anyone can enjoy. We hope that the text will not just explain what it is you are seeing in these images but might also deepen the visual experience. We agree with the famous physicist Richard Feynman that scientific understanding does not diminish a sense of wonder and delight, but on the contrary may enhance it. Affronted at the suggestion of an artist friend that the scientist "takes apart" a flower and renders it "a dull thing," Feynman responded:

> I can appreciate the beauty of a flower. At the same time, I see much more about the flower than he sees. I could imagine the cells in there, the complicated actions inside, which also have a beauty. I mean it's not just beauty at this dimension, at one centimeter; there's also beauty at smaller dimensions, the inner structure, also the processes. The fact that the colors in the flower evolved in order to attract insects to pollinate it is interesting; it means that insects can see the color. It adds a question: does this aesthetic sense also exist in the lower forms? Why is it aesthetic? All kinds of interesting questions, which the science knowledge only adds to the excitement, the mystery and the awe of a flower. It only adds. I don't understand how it subtracts.

We will sometimes invite you to regard the visual wonders in these pages in terms of *atoms doing things*—organizing themselves, exchanging and rearranging their electrons, bouncing off one another, or scattering light. We can't see those processes directly, but we can infer them and deduce their consequences. It's the peculiar power of chemistry to connect those two aspects—the atomic and the everyday—that makes it both a glorious and a useful science, a discipline that reveals how the world we experience emerges from one that is altogether stranger, more elusive, and in some sense mysterious. The words of another great scientist, Charles Darwin, while coined in a different context (to describe the evolution of life on earth), are entirely apposite here too, and Darwin would surely have approved of how they may speak to the unity of the sciences as well as the splendor of the natural world they describe:

> There is grandeur in this view of life˜.˜.˜. whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been and are being evolved.

Fire burn and cauldron bubble." As the witches of *Macbeth* testify, bubbles are a sign of things afoot, of trouble brewing: something is *going on* in that mixture.

The frothing flask is a universal symbol of ominous chemistry, the prelude to a Jekyll-and-Hyde ransformation.

At the same time, who can truly be disturbed by *bubbles*? They are the playful agents of fun—t's no wonder someone in high spirits is said to be effervescent. No "kitchen chemistry" kit is complete without a spectacular display of frothing: dump baking soda into vinegar and you're off, the bubbles spilling from the test tube with volcanic, fizzing abandon. The reaction announces: *this is chemistry!*

What's the fascination? Perhaps it has something o do with the unexpected, with the way that these seemingly innocuous and even familiar ingredients hold the potential for drama. And yet what a simple hing a bubble is: a gas released into a liquid, opening up a spherical cavity for itself and pushing back on he fluid that surrounds it.

When baking soda meets vinegar, where does his gas come from? We start with a powdered solid and a liquid, but their chemical combination releases what alchemists once called (that evocative word again) a "spirit," invisible in air but glistening like a pearl in water. As in all chemical transformations, here is a rearrangement of elements as the atoms abandon old unions and form new ones. Bubbles are he evidence of this change.

Let's look more closely. Vinegar is a solution of acetic acid: a molecule, made from carbon, oxygen, and hydrogen atoms, that may split in water into a ragment called an acetate ion and a hydrogen ion. "Ion" here means that the fragments have electrical charges—in this case, negative and positive respecively. More about them later.)

Baking soda is sodium bicarbonate (also called sodium hydrogen carbonate), an alkaline substance or "base." When it is dissolved in water, it falls apart into sodium and bicarbonate ions; the latter can soak up hydrogen ions. The substance that results from their combination, called carbonic acid, has a tendency to split another way, making a water molecule and a molecule of carbon dioxide (CO_2). *This* is the gas that fills the bubbles.

Carbon dioxide itself dissolves in water to some extent. That's how carbonated water—so-called mineral water—is made. If water contains a lot of dissolved carbon dioxide, some of it undergoes the reverse chemical reaction to the one we just described: it combines with water to form carbonic acid, which in turn falls apart into bicarbonate and hydrogen ions, increasing the concentration of hydrogen ions and turning the water acidic. The invigorating "sharp" flavor of carbonated water comes from its acidity—that sharpness is a common feature of dissolved acids. Carbonated water is made by forcing carbon dioxide to dissolve in water, injecting it under pressure and then maintaining that pressure by sealing the water in a can or bottle. The water is then "supersaturated" with dissolved gas—it is loaded with more of it than it can hold on to under ordinary pressure. When the container is opened and the pressure released, some of the dissolved carbon dioxide gas is released from the solution and forms bubbles: that's the fizz.

This reaction of acids and bases is a common and fundamental one in chemistry. It's not simple, though. For one thing, the process can go either way. Making lots of carbonic acid leads to the release of carbon dioxide as it falls apart. But loading up water with carbon dioxide runs the process the other way, forming carbonic acid and then hydrogen ions. The reaction is reversible.

So how does it "know" which way to go? This depends on where we start from. You could say that reversible chemical reactions are perverse, because they run in a way that counteracts the conditions we try to impose. If we shove in a lot of hydrogen and bicarbonate ions, we generate carbon dioxide from their combination. If we pump carbon dioxide into the water, it reacts to make carbonic acid and thence hydrogen ions. As with a sausage-shaped balloon, squeeze a reaction at one end and it bulges at the other, and vice versa. There's a name for this: Le Chatelier's Principle, after the nineteenth-century French chemist who proposed it. We might phrase it this way: When a chemical system is disturbed by some change, it will adjust to diminish that change. Of course, there's no intention involved in that behavior; it's just how nature finds the ideal balance, the most apt state of equilibrium.

"Carbon dioxide makes water more acidic, so the oceans are becoming increasingly acidified."

Bubbles in a soft drink

The action of an acid on a seashell (calcium carbonate) produces carbon dioxide

much too small to see with the naked eye, with a surface dividing gas from liquid. That convergence of molecules relies on chance encounters, but there's one crucial consideration. If the bubble is to get bigger, its surface must grow. But surface tension tries to pull the surface smaller. It's only when the bubble grows above a certain size—typically about two thousandths of a millimeter across—that it can avoid being collapsed again by surface tension, and will keep growing.

This process of so-called bubble nucleation can be helped if the bubble forms on a solid surface of some kind, which lowers the energy barrier to growth created by surface tension. Bubbles in chemical reactions, and also in liquids supersaturated with dissolved gas, are often initiated at surfaces. They tend to appear at irregularities like scratches, where the surface itself has an abnormally high surface energy, making it an attractive place for gas molecules to congregate into a bubble.

Bubbles in champagne often emerge in a steady stream from some point on the surface of the glass flute. It's often thought that the source points must be tiny scratches, but in fact they are usually bits of material stuck to the glass: dust particles, maybe, or tiny fibers from the paper or cloth used to wipe the glass dry. They are to all intents a kind of "useful dirt" on the glass. A perfectly clean, smooth champagne flute, appealing though it might sound, wouldn't allow champagne to bubble within it.

Why does a whole train of bubbles issue forth, though? Gas builds up at the bubble nucleation site at a constant rate, but only once a bubble reaches a certain size is its buoyancy strong enough to pull it from the surface—at which point a new bubble will start to form until it too reaches that size.

Some bubble trains rise straight up through the liquid. But sometimes bubbles wobble and zigzag as they ascend. This happens because of the effects on the bubble of flow in the liquid around it. One factor is the influence of a bubble on the one behind it: as the rising bubble pushes the liquid out of the way, the flow can disturb the ascent of the next bubble in a way that gets more and more exaggerated, causing bubbles to veer and swerve. Also, large bubbles (a few millimeters across) can get squashed and deformed by the pressure of the surrounding liquid, creating complex wakes in the liquid that may transform a vertical rise into a spiraling or zigzagging one.

Once it reaches the top of the liquid, a bubble bursts, although not necessarily right away: clusters of bubbles can accumulate at the surface like a tiny clump of foam. Eventually the cap of liquid covering the bubble drains to the side and the topmost film becomes too thin to withstand the pull of surface tension. It bursts with an audible pop, producing that deliciously seductive fizzing sound.

This bursting is an amazingly complex process. It creates a kind of rebound in the liquid that pushes up a little vertical jet, like a splash, ejecting a very fine spray of droplets. You can feel these droplets on your lip as you bring it to the liquid surface, giving you a foretaste of the pleasures to come.

There's a yet more important result of this bubble-bursting, as far as your gustatory senses are concerned. As bubbles rise up through champagne, they absorb onto their surfaces the organic molecules that give the wine its flavor, such as alcohols and organic acids. These aromatic flavorants get carried on the droplets of the spray to your nose, producing the wonderful scents and flavors of the liquid. In a non-sparkly wine, such flavorants have to be given a helping hand to escape the liquid by swirling it around the glass—but champagne comes with its own flavor ejection system. Cheers!

Hydrogen bubbles produced in the reaction between zinc and hydrochloric acid

"As bubbles rise up through champagne, they absorb the organic molecules that give the wine its flavor."

Oxygen from decomposing hydrogen peroxide

There are many chemical routes to making bubbles. One of them, called electrolysis and described in chapter 6, uses electricity to break down water or dissolved compounds into their component elements (which may include gases) on the surfaces of electrodes. Another process uses a "reactive" metal like zinc to convert the hydrogen ions in a solution of acid—sulfuric, let's say—into hydrogen gas. This is called a *displacement* reaction, and it is as if the zinc (chemical symbol Zn) atoms displace hydrogen (H) atoms in a competition to partner up with the sulfate (SO_4) ions. (For simplicity, I'm not indicating here that ions, as we mentioned earlier, have electrical charges. The subscript "4" in sulfate indicates that these ions contain four atoms of oxygen, denoted O, attached to one of sulfur, denoted S.)

We can write the chemical reaction like this, with the initial substances on the left-hand side and the final products on the right:

$$Zn + H_2SO_4 \rightarrow ZnSO_4 + H_2$$

(The truth is that neither the zinc ions nor the hydrogen ions are firmly attached to the sulfate ions; all of them are freely dissolved and dispersed in the water. We might better regard this as an illustration of how zinc atoms form positive ions more readily than do hydrogen atoms.)

Hydrogen gas contains these H_2 molecules, in which the atoms are linked in pairs: the molecules gather into bubbles at the surface of the zinc metal. Many students encounter this reaction as a way to make hydrogen gas, which bubbles off to be collected in a test tube held upside down over the reaction vessel—the hydrogen, which is lighter than air, rises up inside and pushes out the air. It can then be ignited with a flame, producing a satisfying squeaky pop as it burns.

Primo Levi describes, in the chapter "Zinc" of his book *The Periodic Table*, how he was instructed to carry out this reaction in his university course:

> The first day it was my fate to be assigned the preparation of zinc sulfate: it should not have been too difficult; it was a matter of making an elementary˜.˜.˜. calculation and attacking the zinc particles with previously diluted sulfuric acid: concentrate, crystallize, dry with the pump, wash and recrystallize.˜.˜.˜. Take the solution of copper sulfate from the shelf of reagents, add a drop of it to your sulfuric acid, and you'll see the reaction begin: the zinc wakes up, it is covered with a white fur of hydrogen bubbles, and there we are, the enchantment has taken place, you can leave it to its fate and stroll around the lab, see what's up and what the others are doing.

But he made the mistake of doing just that, in particular approaching a "pale, sad" young woman called Rita who was busy with the same task. The shy Levi saw his chance to strike up a conversation. "At that moment between Rita and myself there was a bridge, a small zinc bridge, fragile but negotiable," he wrote.

So much the worse for his neglected experiment—but there was some consolation in the outcome:

> My zinc sulfate ended up badly by concentrating, turned into nothing more than a bit of white powder which in suffocating clouds exhaled all or almost all of its sulfuric acid. I left it to its fate and asked Rita to let me walk her home.

Even we will admit that there are sometimes more important things than chemistry.

I am a chemist and engineer who looks upon the living world with the deepest admiration. Nature, herself a brilliant chemist and by far the best engineer of all time, invented life that has flourished for billions of years under an astonishing range of conditions. I am among the many inspired by the beauty and remarkable capabilities of living systems, the breathtaking range of chemical transformations they have invented, the complexity and myriad roles of the products. I am in awe of the exquisite specificity and efficiency with which Nature assembles these products from simple, abundant, and renewable starting materials.

Where does this chemistry come from? It derives from enzymes, the DNA-encoded protein catalysts that make life possible—molecular machines that perform chemistry no human has matched or mastered.

Equally awe-inspiring is the process by which Nature created these enzyme catalysts and in fact everything else in the biological world. The process is evolution, the grand diversity-generating machine that created all life on earth, starting more than three billion years ago. Life is the greatest chemist, and evolution is her design process. Biological systems are good models for sustainable chemistry that uses abundant, renewable resources and recycles a good fraction of its products. I dream of the day when much of our chemistry becomes genetically encodable, and microorganisms and plants are our programmable factories.

Frances Arnold
Nobel Laureate in Chemistry, 2018

Crystals of copper sulfate

Sodium chloride crystals in polarized light

If, in times gone by, you shared the suspicion of the ancient Greek philosopher Plato that nature is governed by geometry, then the shapes of crystals seemed to offer confirmation. Why otherwise would they develop those flat, smooth planes, intersecting at crisp, perfect angles? Why would all crystals of table salt (the compound chemists now call sodium chloride) choose to grow as cubes, while quartz (silicon dioxide) forms prismatic columns tipped with pyramids?

Pondering this question in the early seventeenth century, the German astronomer and mathematician Johannes Kepler was forced to suppose that nature possesses what he called a "formative faculty," with a preference for geometric order—and that "she knows and is practiced in the whole of geometry."

A crystal of sodium thiosulfate in polarized light

"The sheer beauty of crystals is a balm in itself. Why look for more magic than that?"

Today we have no need to fall back on such a vague, mystical idea—but that is partly thanks to Kepler himself. In contemplating the shapes of snowflakes and the cause of their "six-cornered" pattern, he wondered if the geometrical appearance might stem from a regular packing together of spherical "globules" of congealed water (in other words, ice), like the stacks of cannonballs commonly found on the decks of galleons.

Such arrangements are perhaps more familiar today from the packing of snooker or pool balls in the triangle at the start of a game. Fifteen of them fit exactly, and the balls in the center are each surrounded by exactly six others in a hexagonal arrangement.

You can place another layer of balls on top of the fifteen in the triangle, each ball resting in the