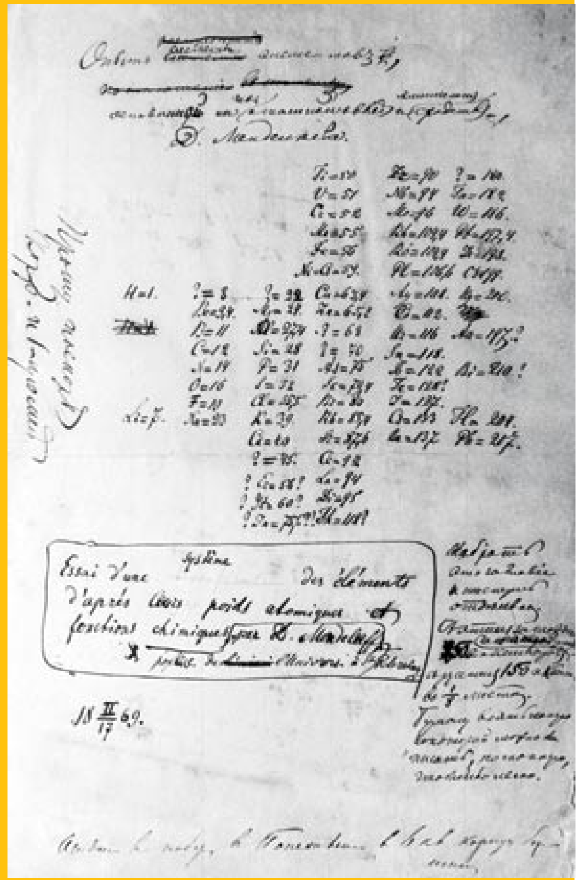
Cherry Picking the Periodic Table:
A New View of Life

By James Trefil

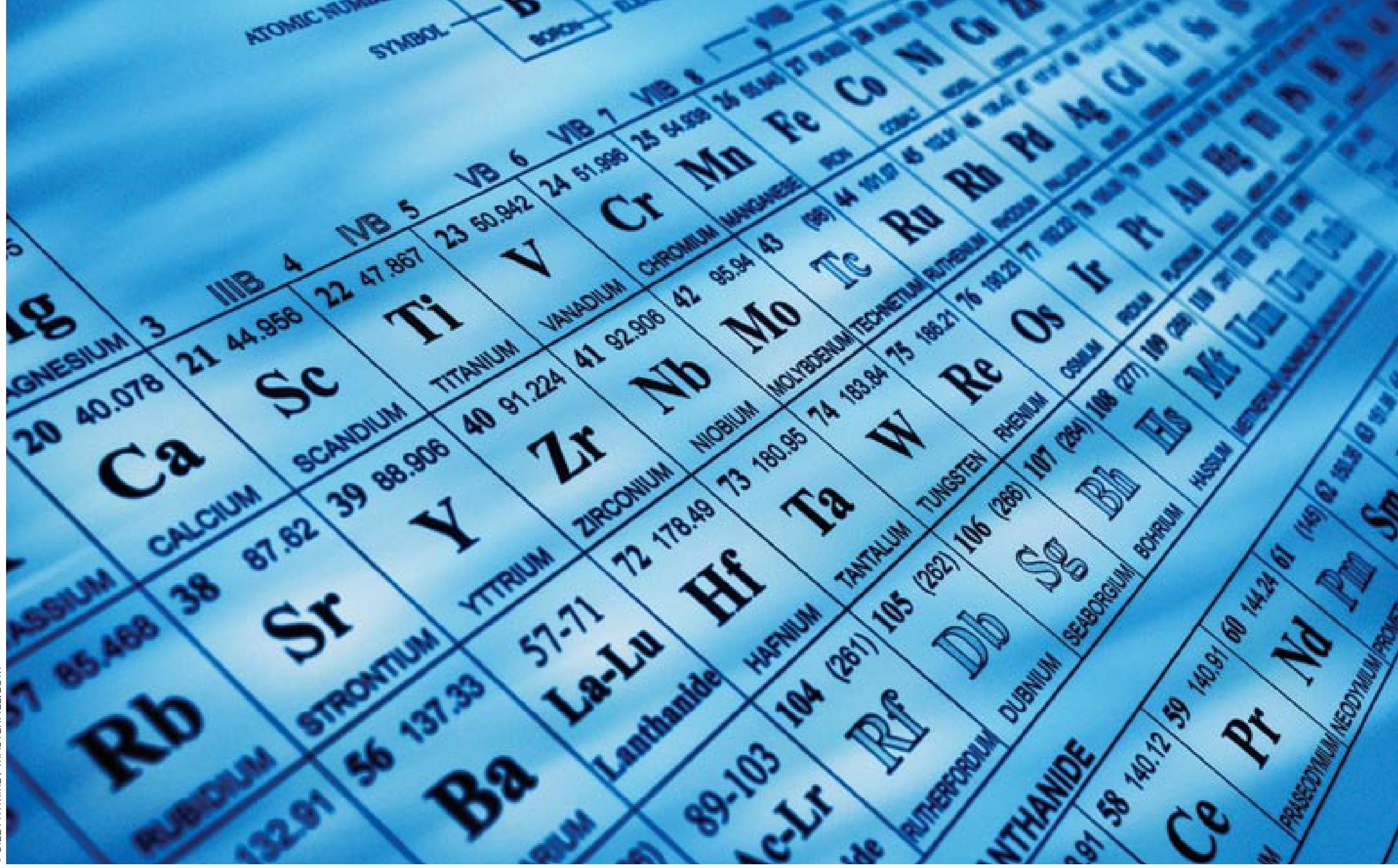


This is the first version of the periodic table, drawn in 1869 by Dmitri Ivanovich Mendeleyev. He left gaps in the table for new elements, which were indeed later discovered, vindicating his theory.

The periodic table of the elements is a beautiful thing. It was first written down in 1869 by the Russian chemist Dimitri Mendeleyev, a professor in St. Petersburg. Mendeleyev had an interesting life—born as one of 14 children to a family in Siberia, he was such a precocious student that the entire family moved to St. Petersburg so that he could attend the university. Later, after his work had achieved international attention, he went through a divorce and remarriage. Technically, this made him a bigamist in the eyes of the Orthodox Church, a situation which is supposed to have prompted the Czar to declare, "Mendeleyev may have two wives, but I have only one Mendeleyev!"

The periodic table is one of those organizational schemes that demonstrates the fact that the universe has an underlying simplicity, despite its apparent complexity. It lists all of the known chemical elements (118 and counting at this time) in an orderly way. Read from left to right in any row and the elements progressively increase in atomic number. Look at the entries in any column and you find elements with similar chemical properties. Mendeleyev arrived at this way of organizing the elements after years of trying to make sense of the seemingly chaotic assortment of chemical elements that had turned up in the 19th century. He had no idea why the table seemed to make sense, or why it predicted the existence of then unknown elements such as germanium and scandium (they showed up as gaps in his orderly arrangement). Understanding why the table is the way it is would have to wait for a half century—for the discovery of the structure of the atom and the development of modern quantum mechanics. Nevertheless, the table gives us a list of the basic building blocks from which the universe is made.

And today, if new ideas put forward by Harold Morowitz of George Mason University and the Santa Fe Institute are right, the periodic table may turn out to play an important role in addressing another fundamental question—the question of how life evolved on our planet. To see what Morowitz is getting at, we have to remember that, at bottom, life is based on chemistry, so that when we talk about evolution, we are really talking about how things arranged themselves so that certain atoms attached themselves to each other and interacted with other groups of atoms. To know how life developed, in other words, we have to start by knowing how atoms and molecules came to interact with each other as they do in living systems.



This contemporary version of the periodic table has the elements arranged in blocks set in columns.

And that's where the periodic table comes in. Think of it as a kind of giant Home Depot, with bins that contain all the materials necessary to build everything around us, including living systems. Each bin is labeled with the name of an element—hydrogen, carbon, ytterbium, and so on. Some of the bins, like hydrogen, are huge, holding a significant amount of all the material in the universe. Other bins, like ytterbium, are small, and represent less abundant substances. But large or small, what's in these bins is the stuff from which the entire universe is made. The question that Morowitz wants to ask is simple: Why does life seem to use some building materials more than others? Why, in other words, does life seem to require more from some "bins" in the periodic table than from their neighbors?

There are actually two parts to this question. The first part asks what elements actually appear in living systems, the second asks why those particular elements are used and not others. Let's start with the first part. In the table below, we see some common chemical elements, together with the percentage (by weight) in which these elements are found in the universe at large, in the Earth's crust, and in the human body (which we will take as a proxy for living systems in general).

Two things leap out at us from this table. The first is that a massive winnowing of elements took place when the Earth formed—the mix of elements on our planet isn't much like the mix in the universe at large. More importantly for this discussion, though, we can see that yet another winnowing took place when living systems formed, because elements found there (carbon and iron, for example) are not particu-

BELOW: Like a grocer adjusting his pile of fruit to suit his customers' needs, nature has, over time, shifted the mix of atoms in living systems to make them better competitors.

larly common even on Earth. In fact, scientists have long known that living systems are made almost entirely of a few elements—carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur (a convenient mnemonic is CHNOPS). To these we add some elements common in seawater, like sodium and calcium, and a few trace elements, and that's pretty much it. So why, Morowitz asks, are these the chosen "bins"?

For some elements, the answer is obvious. For example, one of the basic requirements of life is that there has to be some way to transfer information from one generation to the next—the job done by DNA in living systems on Earth. Carbon is an atom that can be formed into long, complex chains, and hence can be used to form the backbone for information-carrying molecules. Go down one row in the periodic table and we find silicon, an atom that has properties similar to carbon and, one would think, could serve as the basis for an alternate form of "DNA." Indeed, silicon-based life has been a staple of science fiction for years. Unfortunately, when you look at the properties of silicon in detail, it just won't work. For one thing, the bonds formed between silicon atoms tend to be weak, and even when chains are formed, they tend to be unstable in the presence of water and oxygen. This makes them poor choices for an alternate biochemistry.

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For other elements, however, the reason for the choice is less obvious. Morowitz proposes a simple answer to this question: fitness, or, in his words, "fine tuning." To understand how this works, think of a simple analogy. Imagine that you are a grocer who wants to make a pile of citrus fruit for your customers. You start with crates of lemons, oranges, grapefruits, limes, and so on. Imagine further that each piece of fruit has little Velcro patches that allow it to attach to others.

In the beginning, you might just put together a pile from the biggest box—all oranges, for example. You would quickly learn, however, that your customers wanted more than oranges, and you would start arranging your piles of oranges so that you could fit in grapefruit and lemons. Later, you might learn that the Velcro on the ordinary grapefruits was too strong, so that customers had a hard time taking them off the pile, but that the Velcro on pink grapefruit didn't create this problem. Over time, then, your pile would come to have only pink grapefruit. Eventually, driven by the desire to maximize your sales, the pile might come to have proportions of citrus quite different from the proportion in the boxes from which the pile is made.

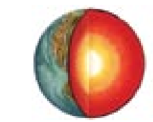
In the same way, Morowitz argues, over billions of years living systems have fine-tuned their molecules in response to their environment, driven by the inexorable pressure of natural selection. Like the grocer adjusting his pile in response to customer demand, nature has, over geological time, shifted the mix of atoms in living systems to make them better competitors.

That life should be based on the CHNOPS atoms isn't too hard to understand—they are reasonably common on Earth and form multiple chemical bonds easily. In terms of our analogy, they come in big boxes and have big Velcro patches. But once we get past these simple atoms, Morowitz's "fine tuning" begins to operate with a vengeance. In the chemical maelstrom we call the cell, tiny differences in the efficiency of a chemical reaction can have a huge effect on the ability of the cell to reproduce. And just as a slight customer preference for lemons in our analogy will quickly produce more lemons in the citrus pile, a slight advantage in reaction rate will allow the cell that has it to outcompete, and eventually eliminate its competitors.

Morowitz points to an interesting example of this effect. It turns out that all mammals require selenium as a trace element (it forms part of complex molecules that govern the processes by which toxic materials are removed from cells, increasing the efficiency of those processes). Selenium is below oxygen and sulfur in the periodic table, which means it has similar chemical properties, but it is relatively rare (it's concentration in the Earth's crust is only one ten-millionth that of oxygen). Nevertheless, because some ancestral organisms containing selenium were slightly better at surviving then those that were not, today we all need it. In fact, a rare heart condition in humans called Keshan's syndrome is caused by a lack of the element. And oddly enough, there are even a few obscure bacteria in which experimenters have found that selenium can be replaced by tellurium, the next element in that column in the periodic table. This kind of experiment may eventually tell us something about how life works its way down the periodic table.

The necessity of trace elements in living systems can sometimes lead to surprising situations. For example, a number of years ago in Australia, sheepherders were puzzled when large numbers of their flocks sickened and died when grazing in a particular area. Investigators eventually found that the soil in that area was severely depleted in cobalt, an element that plays a role in the chemistry of vitamin B12. Plants can thrive without cobalt, but mammals cannot, as the sheepherders learned to their cost. (Feeding the sheep cobalt supplements eventually solved the problem.)

"What we learn from the periodic table," Morowitz says, "is that life is always conducting chemical experiments, trying to find that small advantage. It doesn't matter how difficult it is to find the element you need—life will make the effort to incorporate it."

ELEMENT	 UNIVERSE	 EARTH CRUST	 HUMAN BODY
H Hydrogen	74	1.5	10
He Helium	24	0	0
C Carbon	.005	0.01	18
O Oxygen	.01	46	65
Fe Iron	.001	6.2	<.05
Ca Calcium	.0007	4.6	1.5

NEBULA, EARTH CORE: COURTESY OF NASA/JPL; BODY: © DENIS AGLICHEV/ISTOCKPHOTO.COM

Common chemical elements together with the percentage (by weight) in which they are found in the Earth's crust, and in the human body. It's evident that a massive winnowing of elements took place when the Earth formed, and yet another took place when living systems formed.

This way of looking at life and the periodic table is new—as you read this, SFI scientists have been thinking about it for only a few months. Thus, it is difficult to imagine where it will lead. We know that each atom, each obscure element, has a story to tell us about how it came to be incorporated into living systems. At the very least, when we know these stories we will have filled in another piece of the marvelous tapestry of evolution. And maybe—just maybe—in uncovering these stories, we'll find something completely new and unexpected. That's the beauty of basic research.

Stay tuned! ◀

James Trefil is Clarence J. Robinson Professor of Physics at George Mason University and a member of the FIBR project. His latest book is Why Science?