Misconceptions of Science: Is Silicon-based Life Possible?

FROM THE LECTURE SERIES: UNDERSTANDING THE MISCONCEPTIONS OF SCIENCE

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We know that carbon is one of the key, if not the most important, components of all living organisms, including humans. And, because silicon and carbon share certain chemical similarities, it has led to science fiction authors floating the possibility of silicon-based life. Is there a kernel of fact in that fiction, is it just theoretically possible, but practically unlikely? Or is it simply a figment of a fertile imagination?

Carbon forms four bonds with hydrogen to create CH_4 or methane. It is this ability of carbon to make four atomic bonds with other elements that makes life possible.
(Image: VectorV/Shutterstock)

Carbon Is the Basis of Life on Earth

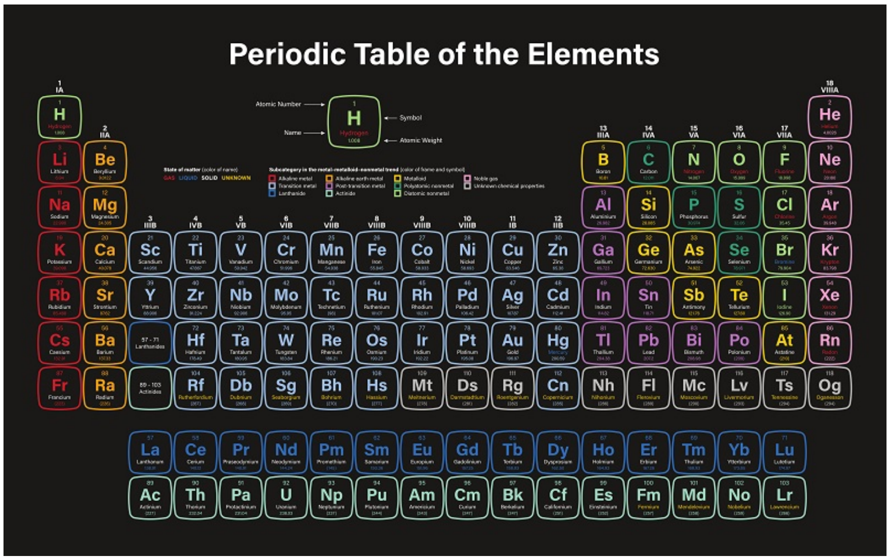
Life, as we know it, is based on the element carbon. Although, it’s not completely carbon. For example, you, or maybe a piece of fruit you ate for breakfast, is not entirely carbon. You contain other elements as well. You contain oxygen, hydrogen, nitrogen, calcium, and phosphorus—a whole bunch of chemicals. In fact, those six elements make up 99% of your body. It turns out that, by weight, oxygen is the most common element, about two thirds. That’s because blood has a lot of water and oxygen is a heavy component of water.

Carbon is the second most common, and it is carbon that dominates the chemistry of life. The reason for this is actually incredibly fascinating. It really boils down to chemistry; and to understand how this works and why silicon is considered to be an alternative to carbon as a core element of life, we need to turn to our periodic table of elements.

Learn more about what’s inside atoms.

Deep-Dive Into the Periodic Table

The periodic table is organized in the following way: all elements in the same column react in similar ways and, as you go from the top to the bottom, the elements go from light to heavy.



The carbon group in the periodic table comprises carbon (C), silicon (Si), germanium (Ge), tin (Sn), lead (Pb), and flerovium (Fl). All these elements can form four atomic bonds. (Image: Humdan/Shutterstock)

The column to the extreme right contains what are called the noble gases: helium, neon, argon, krypton, xenon, etc. Their defining feature is that they don’t interact with other elements. On the far left, we find what are called the alkali metals: hydrogen, lithium, sodium, potassium, etc. They are incredibly reactive.

The reason why each column has different reactivity has to do with the configuration of electrons surrounding them. The electrons surrounding atoms are in a series of what are called orbitals. In the most simple terms, these orbitals are a little like cups and the electrons are like marbles. You can put marbles into the cup until the cup is full, at which point, the cup doesn't want any more marbles.

Following this analogy, the full cups correspond to the noble gases. These atoms have all the electrons they want and so they don't interact with others. Now chemical bonds are just atoms sharing electrons, so if an atom doesn't have a full orbital, it can accept electrons from other atoms, just like a cup with a missing marble could take a marble from another atom.

So, let's consider the column of atoms next to the noble gases. This column contains fluorine, chlorine, bromine, iodine, etc. The elements in this column don't quite have a full cup. It's as if they're missing a marble. Accordingly, they can accept one marble from some other cup. Or, atomically-speaking, they can accept an electron. In chemical terms, elements from this column can make one bond with other elements.

Hydrogen is the simplest element with one marble to spare, so we can use it as a way to illustrate the way that elements connect. For instance, when fluorine, which is at the top of the column, interacts with hydrogen, you get hydrogen fluoride, which is denoted by the symbol HF, which is one hydrogen atom and one fluorine atom.

What happens when you move one column to the left, to the column with oxygen, sulfur, selenium, etc.? Well those elements are missing two electrons, like a cup without two marbles. These elements can make two atomic bonds. In fact, when we think about connecting hydrogen to oxygen, we see that oxygen can connect to two hydrogen atoms to make H20, or water.

The next column, with nitrogen, phosphorus, arsenic, antimony, etc., the pattern continues, this time with three missing electrons. Nitrogen can make three bonds with hydrogen, making NH_3 or ammonia. And when we get to the column containing carbon, silicon, germanium, and tin, we have elements that can make four atomic bonds. Carbon, combined with hydrogen, makes CH_4, or methane. Methane is a key component of natural gas. But the key thing here is that elements in this column can make four atomic bonds.

Let's continue the analogy with the next column with boron, aluminum, gallium, and indium. The analogy clearly would suggest that these elements could make five bonds and there is some truth to that. However, embracing our analogy firmly, as we move more and more to the left, the situation starts to look less and less like a cup missing a few marbles to looking like a smaller cup with a few too many marbles sitting on the top.

So, rather than being atoms that accept electrons (or cups accepting marbles), they become more like atoms that donate electrons to other atoms. At some level, it's why a lot of chemistry involves atoms on the left side of the periodic table interacting with atoms on the right. Just because some cups have some marbles to give and some need some marbles to fill up.

I do need to remind you that the cup analogy is just that, an analogy. It's very clearly imperfect and a chemist will tell you that it glosses over a lot of important points. And they're right. But the analogy hopefully served its purpose and helped you understand how the various columns are similar at an atomic level. This is crucial to understanding why people say that silicon-based life is possible.

> *This is a transcript from the video series **Understanding the Misconceptions of Science**. Watch it now, Wondrium.*

The Bonds of Carbon

So, now that we know that carbon can make four bonds, we're beginning to understand why life is based on carbon. Carbon is an amazing and versatile element, because of its ability to make four atomic bonds with other elements. Why these four atomic bonds are important can be better understood when we take a look at organic molecules compared to inorganic ones.

For inorganic molecules, you have the hydrogen molecule (which is H2), or ammonia (NH_3), or water (H_2O). With these elements, you can see a handful of atoms connected together by a couple of bonds.

Now let's look at organic molecules. They are crazy complex. I mean, there's caffeine, with a formula of

C8 H10 N4 O2. There's theobromine, which is the bitter alkaloid that makes people like chocolate, with its formula of C7 H8 N4 O2. And these are, in fact, the less complex carbon-containing molecules. The vitamins like B12, or hemoglobin, or even DNA (yes, it is a molecule) are ridiculously complicated.

In order to make such complex structures, it's crucial that molecules are involved that can make lots and lots of bonds. And that's why carbon makes life possible.

Learn more about what the world gets wrong about science.

Is Silicon-Based Life Possible?

Why do people think that silicon-based life may be possible? The reason is simple. Silicon is below carbon on the periodic table and silicon can also make four bonds. So, it stands to reason, you could just as easily make complicated molecules with silicon. That makes perfect sense, except it's not true. Why is that?

Silicon, in the form of silicate minerals, makes up 28% of the Earth's crust, which is about 1,000 times more than carbon. (Image: Tanya Kalian/Shutterstock)

So, let's contrast silicon and carbon. They can both form four bonds. On Earth, silicon is far, far, far more prevalent than carbon. Basically, silicon is found in sand and rock. In the Earth's crust, silicon makes up 28%. Carbon, in contrast, is about 1,000 times less common. Yet carbon makes up life, while silicon doesn't. If silicon were a contender, the fact that it is so common would give it a huge advantage.

So why does silicon fall short? Well, to begin with, when carbon makes four atomic bonds with all of its neighbors, the bonds tend to be of the same strength. In silicon, the first bond is much stronger than the others, which means the first bond is far more stable than the others.

It's because the first bond is formed when the electrons from each atom reach directly to the other atom in a metaphorical handshake. The other bonds are formed from electrons that are further away and they effectively don't get as good a grip.

Another thing is that when carbon connects with other chemicals common in organic molecules, the bonds are of similar strength. Carbon–carbon, carbon–oxygen, carbon–hydrogen, and carbon–nitrogen are all pretty similar. That means that, from an energy point of view, it is pretty easy to swap out atoms, which is the physicist's way of saying that chemical reactions occur.

However, the silicon–oxygen bond is much stronger than say silicon–hydrogen, or silicon–carbon, or even silicon–silicon. That means that once silicon interacts with oxygen, it's very hard to break them apart. This makes the ease and versatility of silicon chemical interactions far lower than the ones involving carbon.

And, about that silicon–oxygen bond compared to the carbon–oxygen one. When you breathe, you take in oxygen and breathe out carbon dioxide, which is given by the chemical formula CO2. The corresponding silicon molecule is SiO2 or silicon dioxide. The more common word for that chemical compound is 'rock'.

Thus, a silicon-based creature using oxygen as part of its energy cycle would be breathing out sand. This isn't a new realization. In 1934, science fiction author Stanley Weinbaum wrote a story in the pulp fiction magazine called *Wonder Stories* of an expedition to Mars. The astronaut encountered a life form that was gray, with one arm and a mouth that extruded bricks. He realized that the bricks were the product of the creature's respiration.

So, while a simple understanding of the chemistry of carbon and silicon suggests that silicon-based life is possible, if you dig a bit deeper, it seems that silicon-based life isn't really all that likely.

Initially, the chemistry seems compelling, but I think that the most compelling argument for the advantages of carbon is simply the fact that life on Earth is made of carbon, in spite of there being far more silicon around. If silicon were competitive, a silicon-based lifeform here would have come into existence and outcompeted our ancestors.

Common Questions about Carbon, Silicon, and Silicon-Based Life

Q: Where is silicon mostly found?
Silicon has a significant presence on Earth. In fact, it makes up 28% of the Earth's crust, which is about 1,000 times more than carbon.

Q: What is silicon-based life?
For a long time, science fiction authors have floated the possibility of silicon-based life as an alternative to carbon-based life, to explore the possibilities of life on distant planets, inhospitable environments, and even deep-space travel. The idea of silicon-based life has most prominently been explored in the Star Trek series, but even before that science fiction author Stanley Weinbaum had written about such a life form in a story in 1934.

Q: Why is carbon better than silicon for life?
Carbon bonds tend to be of the same strength, and while silicon forms a very strong and stable first bond, the others are less stable and strong. So, a carbon–oxygen bond, being of similar strength to other carbon bonds, can easily swap out atoms, resulting in a chemical reaction. In the case of silicon, the silicon–oxygen bond—the first bond—is so strong that it's very hard to break them apart. This makes the ease and versatility of silicon chemical interactions far lower than the ones

involving carbon. This is the reason why carbon is the basis of life and not silicon.

Q: Why can't silicon replace carbon?
The carbon–oxygen bond is more suited to life than the silicon–oxygen bond, besides just the differences in strength of the bond or the ease of chemical interactions. When we breathe, we inhale oxygen and exhale carbon dioxide. The chemical formula for carbon dioxide is CO_2. The corresponding silicon molecule is silicon dioxide, or SiO_2, which is commonly known as rock. So, silicon-based life on Earth would be breathing out sand.

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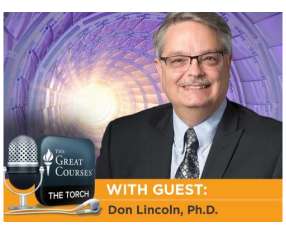

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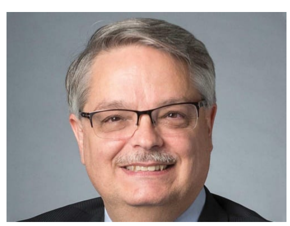

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