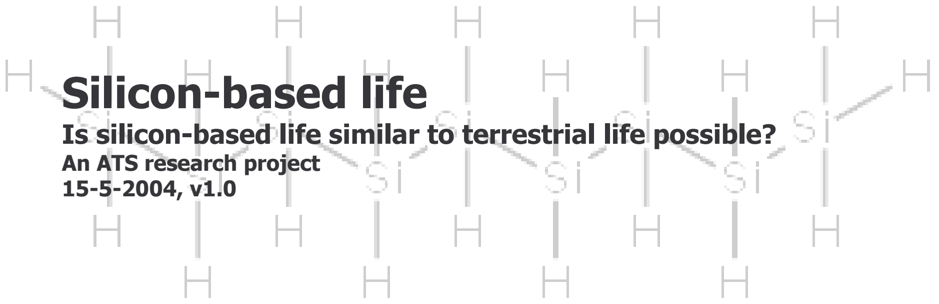

Silicon-based life

Is silicon-based life similar to terrestrial life possible?

An ATS research project
15-5-2004, v1.0

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Contents

Introduction

In the search for extraterrestrial life, scientists and science fiction writers have proposed life based on the element silicon, instead of life that is based on carbon, like the life on earth. This article will research the possibility of silicon-based life. It will focus on life with a molecular design similar to terrestrial life. We have decided to do this, because it is very difficult to come up with a totally different structure of life than life as we know it. We need something to model our silicon-based life after. In a section at the end of the article (section 9) we will devote some time to the possibility of these totally different kinds of life, but these will not be the main focus of the project, because we can't say much scientific about them. They are only speculation and we want hard facts.

All the sources we have used for this article have been added in section 11. The text references to this sources which are shown in superscript: e.g. [3.1].

Abstract

Once you have the formation of complex molecules you can have the complex chemical pathways required for life. Required properties for life are: long chains, double and triple bonds, handedness, rings, stable molecules with other elements, metabolism, energy storage, molecules that store information and a chemical equilibrium of the substances needed for the organisms.

Silicon has problems with two of these properties (and ironically, the most important ones): long chains and a chemical equilibrium. The first problem can be solved by proposing a silicon-oxygen hybrid polymer, but the second problem can not be solved without some unproven speculation.

An environment as needed by silicon-based life similar to terrestrial life already exists and is known as earth. There is no silicon-based life on earth though and therefore it seems that the problems with silicon-based life can’t be solved.

Abbreviations

ADP	adenosinediphosphate
ATP	adenosinetriphosphate
ATS	AboveTopSecret.com
C	carbon
Ca	calcium
Cl	chlorine
DNA	deoxyribonucleic acid
GRB	gamma-ray burst
H	hydrogen
K	Kelvin (temperature unit)
mRNA	messenger RNA
N	nitrogen
Na	sodium
O	oxygen
P	phosphor
P_i	inorganic phosphate group
RNA	ribonucleic acid
S	sulphur
Si	silicon
tRNA	transfer RNA

1 An introduction to chemistry

We understand that not everyone reading ATS has knowledge of chemistry. That’s why we decided to put in a section with a small introduction to chemistry. If you already know chemistry, you can skip this section. The text references to some better introductions on the internet.

We generally recommend to keep a periodic table handy when you read this article. A good one can be found at http://www.webelements.com/.

1.1 What are you made of?

Chemistry is the science of matter on the scale of atoms and molecules. Since we’re talking about silicon-based life like the life on earth, we only need to consider conventional chemistry, not the chemistry of extreme conditions. You can find more extensive introductions on the internet.[1.2]

Everything you see around you is made from atoms. Every atom is a combination of more fundamental particles called protons (charged positively), electrons (charged negatively) and neutrons (without charge, neutral). Atoms have a nucleus containing protons and neutrons and several shells containing electrons.

Atoms come in slightly more than 100 flavours, called elements. Every element has different properties. You probably already know a lot of elements, like helium, oxygen, nitrogen and iron. Every element gets a number based on the amount of protons in the nucleus. Hydrogen has only one, helium two, etc. An overview of all elements can be found at WebElements.[1.1]

The elements are organized in groups of elements with similar properties, like group 18 of the inert gasses (helium, argon, xenon, etc.). In the table of elements, columns designate a group. The similar properties are caused by a similar number of electrons in the outer electron shell, also called the valence shell.

Single atoms, however, are not the only kind of matter. They can combine to from molecules or can give away or get extra electrons. Conventional chemistry has three kinds of matter:

- Atomic, only single atoms without charge.
- Molecular, groups of two or more atoms connected with covalent bonds without charge
- Ionic, atoms or molecules with either a positive or a negative charge.

For life, the molecular kind is the most important. There is an enormous amount of variation between all the kinds of molecules in your body. Your body contains molecules so large that you can actually see them. A single molecule of DNA, when rolled out, is visible to the naked eye as a small white string. It also contains molecules not larger than two atoms, like the O_2 that is dissolved in the cytoplasm of your cells. There are a lot of different combinations of atoms possible and therefore a lot of different molecules all with different properties. Some are stable and some are unstable, some react violently and some don’t react at all, etc. All these properties are determined by what atoms are in the molecule and what structure that molecule has (see section 1.3).

1.2 Chemical bonds

How can two atoms be combined in a single molecule? They are connected to each other with a covalent bond. A covalent bond basically means sharing an electron pair. Covalent bonds come in three kinds: single, double and triple bonds. In single bonds, one electron pair is shared; in double, two are shared; and in triple, three are shared. Quadruple bonds are too unstable too appear.

Every element has a certain number of bonds it can take on at the same time. This is a number from 0 (e.g. helium) to 4 (e.g. carbon and silicon). A single bond counts for 1, a double bond for 2 and a triple bond for 3. Every atom tries to get as many bonds as it's number. A carbon atom wants 4 single bonds or 2 single bonds and 1 double, etc.

What determines how many bonds an atom can have at the same time? Every atom wants a full valence shell, because that is energetically the most stable state. The valence shell is the outer electron shell. Every atom already has between 1 and 8 electrons in the outer shell. It wants to get eight. This can be done by sharing electrons with other atoms and getting extra electrons in the progress. Oxygen can take on two bonds, because it already has 6 electrons in the valence shell. The noble gasses already have 8 electrons in their valence shell and therefore react with almost nothing.

1.3 A systematic notation

In science it is always important to have a general and systematic notation. Chemistry also has a few different names and these are generally not so difficult. I'll only look into nomenclature and structure drawings, but I will not go to deep into organic nomenclature because that is too difficult and not required for this project (source 1.2 has a piece about it, if you're interested).

We can give molecules a simple name by summing up what atoms it is composed of. Every element has it's own abbreviation, which you can find at WebElements[1.1]. Salt has one sodium atom and one chlorine atom, therefore we call it NaCl.

If there is more than one of a certain atom in a molecule, like in carbon dioxide, we use a subscript number to indicate that. Instead of COO, you get CO_2. Charged atoms or molecules are denoted with in superscript first the charge number (or no number, if the charge number is one) and then the sign of the charge. The double positively charged calcium atom is denoted Ca^{2+} and the single negatively charged chloride atom is denoted Cl^-.

If we try to give an organic substance like sugar (α-cyclic D-glucose) a name as described in the paragraphs above, we are not sure anymore what substance we mean exactly. Sugar (α-cyclic D-glucose) would be: $C_6H_{12}O_6$. But this formula could also be β-cyclic D-glucose, β-cyclic D-galactose, α-cyclic D-galactose and other substances. These all have different properties. That's why we usually draw the structure of complex molecules. The substance α-cyclic D-glucose looks like a ring (figure 1.1).

The rules for structure drawing are:

- The main chain carbon atoms are not denoted with a C.
- A single bond is a single, a double bond a double line and a triple bond a triple line.
- The hydrogen atoms attached to main chain carbon atoms are not always drawn.
- Thick/thin lines is used to describe the 3-dimensional structure of the atom. Thick means nearby and thin means further away.

If you keep these rules in mind and count the number of each kind of atoms in the drawing, you get $C_6H_{12}O_6$. These drawing are unambiguous and will be used a lot in this article.

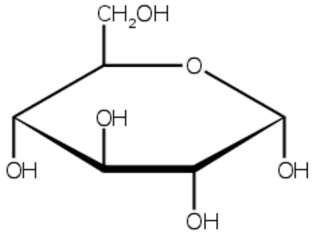

Figure 1.1 α-cyclic D-glucose

2 The history of silicon-based life in science-fiction and science

The first one to seriously propose silicon-based life as an alternative to carbon-based life in the scientific community was the German astrophysicist Julius Schneider.[3.3] He used this theory in 1891 to predict life on all the rocky planets in our solar system. In 1893, James Emerson Reynolds proposed that silicon-based life might exist at extremely high temperatures, because the silicon compounds known at that time were very stable, even at extremely high temperatures. Thirty years later, J.B.S. Haldane suggested that silicon-based life might live in the molten rock inside the earth.[3.6] The mantle of the earth contains enough silicon and, as said before, the known silicon components were stable at very high temperatures. Dr. Tom Gold wrote a book about the possibility of silicon-based life inside the earth.[3.8]

The idea of silicon-based life was featured in a lot of different science-fiction novels, movies and series. Isaac Asimov's essay '*Planets Have An Air About Them*' included a section about silicon-based life.[3.5] There have also been several Star Trek episodes with silicon-based organisms, for example episode 26 from season 1, 'The Devil in the Dark':

"The Enterprise is sent to investigate a string of sabotages and murders on pergeum mining planet Janus 6 (which also possesses an abundance of uranium, cerium, and platinum). Starting 30 monthly previously when the new level 23 was opened, 50 people have been killed in the mines, including the guard Schmitter. All of the murdered mine workers were burned to a crisp. The only solid lead as to the culprit is a large fuzzy object seen briefly by Chief Processing Engineer Ed Appel.

(…)

Spock and Kirk speculate that the creature may be based on silicon instead of carbon, and suggest that if that were the case, then phaser 2 would be much more effective than the phaser 1 used by the miners. They equip a landing party with phaser 2 and go in search of the creature. The creature finds one of the search party, and promptly fries him. Spock examines a nearby tunnel and discovers it to have been newly cut. The creature then shows itself and is fired upon. It escapes, but the blast chips off a chunk of fibrous silicon material which is apparently its skin.

(…)."[7.1] *(this text, denoted with a cursive font, was written by Eric Weisstein, ©1996-2003 Eric W. Weisstein)*

In a recent thread on ATS, some members speculated that the 'grey'-aliens might be silicon-based.[7.2] The authors feel that discussions like these are, although they are amusing, in the end useless, because there is no evidence that these aliens even exist. It is therefore also impossible to know anything about their molecular biology. If we had measurements of their molecular biology, we would already know for sure they exist.

3 What are the special properties of carbon, especially in terms of molecular structures, that make it the basis of our form of life? What is required chemically for life?

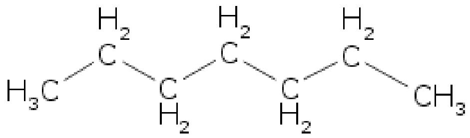

Figure 3.1 Carbon polymer

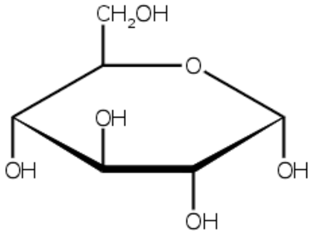

Figure 3.2 Glucose

Carbon is the most versatile element. It can form rings, chains and other interesting molecules. Carbon chemistry is an entire field of chemistry. Basically, life as we know it is based on the elements C, H, O, P, S and N: carbon, hydrogen, oxygen, phosphor, sulphur and nitrogen. There are other elements in our body, but they are not as common or as important as these six. Because of it's versatility, carbon can form very complex molecules. Once you have the formation of complex molecules you can have the complex chemical pathways required for life.

3.1 Carbon forms long chains

Carbon's number one special ability is forming long chains of itself through single covalent bonds. This chains are very stable and can easily be hundreds of carbon atoms long. The structure of these polymers is like this (figure 3.1) and their general formula is C_nH_{2n+2}, where n can be any positive integer.

These chains are the back bone of virtually all organic chemicals required for cell pathways to function. Just take a look at glucose (figure 3.2). It has a central ring of carbon.

Other molecules vital to you that have a simple carbon backbone (as in figure 3.1) are fatty acids and phospholipides (in cellular membranes).

3.2 Double and triple bonds allow rigid chains

The second important feature is that the chain can easily be made into rigid shape. Normally the chain has the structure of a chain of tetrahedrals that are connected at the points. This structure can be rotated around every bond between two connected carbon atoms. Sometimes a certain shape is needed for the molecule to function well, like in most enzymes. This can be easily accomplished by replacing two hydrogen atom with a double bond between the two carbon atoms. A triple bond can also be made by replacing four hydrogen atoms with two extra bonds. You can check that every carbon atom still has four bonds. The structure of such a rigid chain looks like a polymer similar to figure 3.1 (figure 3.3).

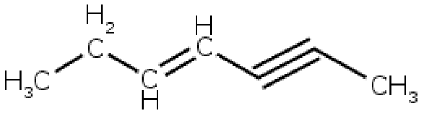

Figure 3.3 A carbon chain with a double and a triple bond

3.3 Carbon supports 'handedness'

Because carbon can form four bonds, usually in a tetrahedral, it can have a property called handedness. The molecules have different properties when they are mirrored. An example is glycogen and cellulose (see section 3.7). The only difference between the molecules is the handedness, but the properties are completely different: cellulose is very rigid, while glycogen is not.[3.7] You can't even digest cellulose without the help of specialized bacteria. Glycogen is no problem at all.

Handedness is very important to enzyme functions, because the substrates fit into the enzyme exactly. The handedness can make the difference between fitting and not fitting. By changing the handedness of molecules with enzymes, the cell can regulate chemical processes.

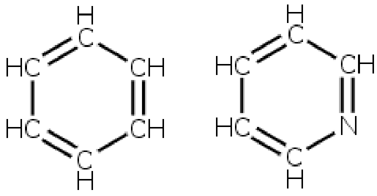

Figure 3.4 A benzene ring (left) and a benzene ring with a carbon atom replaced with a nitrogen atom

3.4 Carbon can form stable rings with itself

One the most important carbon groups is the benzene ring. Six carbon atoms and six hydrogen atoms in the following shape (figure 3.4). Benzene rings (C_6H_6) are important for a lot of hormones (cortisone, progesterone and testosterone all have four rings) and a few amino acids. You can also replace a carbon atom with a nitrogen atom. Then you get the kind of ring that is the basis of all nucleotides (see section 3.5 and section 3.8).

3.5 Carbon combines well with other elements and can form complex molecules

The third important feature carbon has is the ability to bond with other atoms very well, especially the other four elements important to life: H, O, P, S and N. There are two reasons why carbon bonds easily:

- Carbon has a high electronegativity of 2.5. There is not much shielding of the positively charged nucleus by the negatively charged electrons.[1.6]
- Carbon has a small bond length of $77\cdot10^{-12}$ m. This also makes its bonds stronger.[1.6 and 3.2]

This allows for various chemicals to be based on carbon chains. These different molecules have various functions within a cell based on the rest of its chemical makeup. This ability to form complex chemicals makes it the basis for life. Just an overview of some of the different kinds of special groups within a carbon backbone that are vital to life (also see figure 3.5):

- Ethers, with oxygen
- Alcohols, with oxygen and hydrogen
- Aldehydes, with oxygen and hydrogen (oxidized primary alcohol)
- Ketons, with oxygen (oxidized secondary alcohol)
- Carbon acids, with oxygen and hydrogen (e.g. asparagine-acid, an amino acid)
- Alkanoates, with oxygen (rest of carbon acids)
- Esters (e.g. acetylcholine, a very important neurotransmitter), with oxygen
- Amines (e.g. histamine), with nitrogen
- Thiols, with sulphur and hydrogen

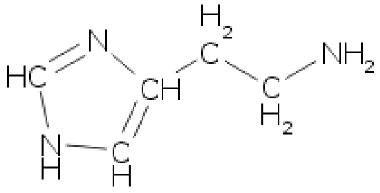

Figure 3.6 Histamine

The ability of carbon to bond with other atoms so well allows for a large variety of stable molecules, including:

- Amino acids, which are the basis of every protein in your body. Protein is probably the most important kind of molecule in your body. They do almost all the chemical work.
- Nucleotides, which are the information carriers in DNA and RNA (see section 3.8). There are eight different kinds and they are all based on carbon and nitrogen: adenine (A) (see figure 3.6), guanine (G), cytosine (C), thymine (T), uracil (U), hypoxanthine (I), pseudo-uracil (Ψ) and dihydro-uracil (UH_2). The first five are the most important because they appear in DNA and mRNA, the others three only occur in tRNA.
- Saccharides, you all know them as sugars. There are three different kinds of sugar, monosaccharides, disaccharides and polysaccharides. Saccharides are broken down in the metabolic pathway to get energy, which is carried by ATP (see section 3.6). Biologists only count 1, 2 and many.
- ATP and ADP, the cells energy carriers. The names stand for adenosinetriphosphate (ATP) and adenosinediphosphate (ADP). They are a combination of a nucleotide (adenine), a monosaccharide (D-ribose) and two or three phosphate groups.

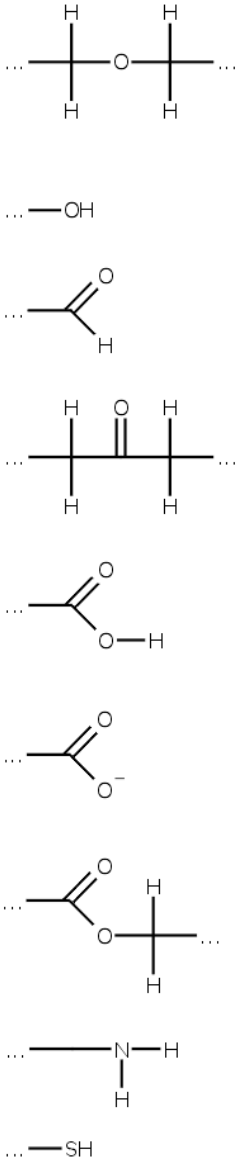

Figure 3.5 The structure of some carbon groups (remember that C's for carbon are not shown, see section 1.3), from top to bottom: ethers, alcohols, aldehydes, ketons, carbon acids, alkanoates, esters, amines and thiols.

3.6 The metabolic pathway

The enormous complexity of carbon chemistry allows for the most important chemical pathway in a cell: the metabolic pathway. Life comes in two flavours on Earth. The first one kind makes its own organic molecules from inorganic molecules: the autotrophic organisms. The second kind makes it's organic molecules from other organic molecules: the heterotrophic organisms.

The autotrophic organisms are the plants and some bacteria. There are two kinds of autotrophic organisms: photo-autorophs, that use light as energy source and chemo-autotrophs, that use certain inorganic chemicals as an energy source. The only way they can use inorganic molecules to make organic molecules is a complex metabolic pathway.

The heterotrophic organisms are all the animals, fungi and most bacteria. They also have a very complex metabolic pathway. The metabolic pathway in animals gets energy from saccharides and stores that energy in ATP molecules. The energy stored in ATP molecules can then be used to make proteins or it can be used by enzymes.

The pathway has three different parts: glycolysis, Kreb's cycle (also called Citric Acid cycle) and oxidative phosphorylation.[2.2] All the parts have a lot of steps that are all regulated by special enzymes. This would not be possible without the complexity of carbon chemistry.

3.7 Energy storage in the form of carbohydrates

Organisms also have to be able to store the energy they get from the metabolic pathway for longer periods. Carbon can form carbohydrates, which store the energy for longer periods. The release of the energy can be controlled by enzymes. Examples of carbohydrates are glycogen in the liver and cellulose in trees.

3.8 DNA and RNA

One thing common to all known life is DNA which, as most know, is a long chain of information. This is vital to every organism and codes for all required proteins. The DNA is read by special enzymes and an mRNA (messenger) molecule is made.

This mRNA chain goes to the organelles that make proteins. There, special tRNA (transfer) molecules adds the right amino acids to the new protein.

The back bone of a DNA or mRNA chain is carbon, the nucleotides are based on carbon and nitrogen, the DNA or mRNA is held together by a saccharide, deoxyribose, and a phosphate group.

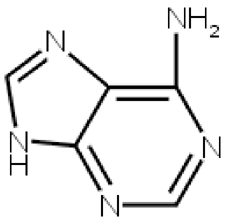

Figure 3.6 Adenine, one of the nucleotides in the DNA and RNA of every organism on earth. Other nucleotides have a similar shape.

3.9 There is a lot of carbon, it's stable and easily accessible

No matter how good carbon is chemically for life, if there's only a tiny bit of it (like Technetium for example) it will never a good basis of life. Luckily for us, carbon is created in the lifecycle of normal stars and supernovae.[5.2] There is a lot of carbon on Earth now, freely available in the atmosphere in the form of CO_2, in organisms and certain minerals.

Carbon is also a stable element. If carbon were like Plutonium, it would decay too fast to form life or kill the life with it's own decay products. The decay products of radioactive isotopes is either α-, β- or γ-radiation. This radiation has enough energy to destroy the bonds between the atoms in molecules.

3.10 Photosynthesis and oxidative phosphorylation support an equilibrium

Plants and other photo-autotrophic organisms get their sugar through a process called photosynthesis[2.3]. The real photosynthesis is a very complicated process with a lot of different enzymes, but we can simplify it to the following simple chemical reaction:

$$6CO_2\,(g) + 6H_2O\,(l) + \text{Light} \rightarrow C_6H_{12}O_6\,(a) + 6O_2\,(g)^*$$

The overall reaction of heterotrophic glucose metabolism is:

$$C_6H_{12}O_6\,(aq) + 36P_i + 36ADP + 6O_2\,(g) \rightarrow 6CO_2\,(g) + 6\,H_2O\,(l) + 36ATP$$

The plants use CO_2 and make O_2, while the heterotrophic organisms use O_2 and make CO_2. This makes sure neither the oxygen or the carbon dioxide runs out and therefore these two reactions form an equilibrium.

4 Why is silicon proposed as an alternative to carbon-based life?

Remember that in section 1.1 we stated that the elements are organized in groups with similar properties? What a surprise, silicon is in the same group as carbon: group 14. This indicates that silicon should have properties comparable with the properties of carbon. Carbon has 4 valence electrons and silicon also has 4 valence electrons.

Quite simply silicon is proposed as an alternative to carbon-based life because it can form many molecular bonds like carbon can. Once you have the formation of complex molecules this allows for complex chemical pathways like we see in living cells. Without the ability to form many different chemicals cells would not be able to have so many complexities and therefore not function as they do.

5 Does silicon have the properties as described in section 3?

In a single word… no. With a bit more nuance… not without unproven speculation, which can be found in section 6.

5.1 Silicon can not form long chains

We'll investigate the silicon analogy of carbon polymers: Si_nH_{2n+2} (see section 3.1 for carbon polymers). Here we find one of the big problems with silicon-based life: Silicon can not form chains like the chains carbon can form. The silicon chains are simply too unstable. Nicholas Linn used numerical methods in Spartan to calculate the bond energy and electron density of carbon and silicon polymers.[3.2] The results can be seen in figure 5.1 and 5.2. It turns out that the electron density is too low, and therefore the bond is too weak to make sure the silicon polymers are stable. Silicon polymers simply don't get any bigger than five silicon atoms. See section 6.1 and following sections for solutions to this problem and the following problems.

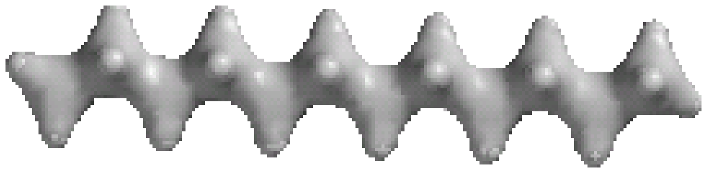

Figure 5.1 Carbon polymer electron isodensity (by Nicholas Linn)[3.2]

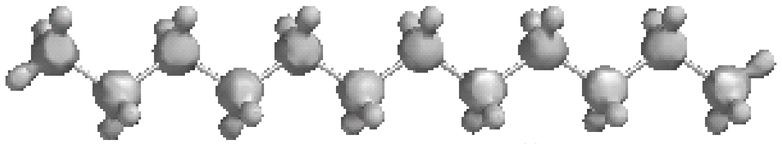

Figure 5.2 Silicon polymer electron isodensity (by Nicholas Linn)[3.2]

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[*] There are also organisms that use H_2S instead of H_2O.[2.3] This does not matter for our discussion, because these organisms are rare and the reason why we talk about photosynthesis is because there are problems with the silicon analogue for CO_2, SiO_2 (see section 5.6 and 6.3).

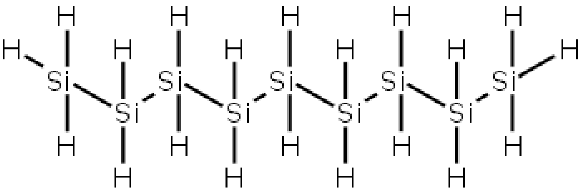

Figure 5.3 The silicon polymer that is similar to the carbon polymer described in section 3.1.

5.2 Silicon can form double and triple bonds

Yes, within the small polymers, silicon can form double and triple bonds. Not that it matters much anyways, because the shape only matters a lot for larger molecules.

5.3 Silicon does support handedness

Because silicon, like carbon, has four valence electrons, its four bonds are arranged in a tetrahedral shape. This allows handedness. This is required for specialized enzyme functions.

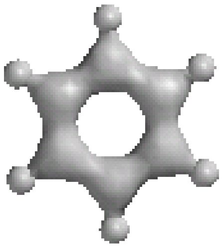

Figure 5.4 Carbon ring electron isodensity (by Nicholas Linn)[3.2]

5.4 Silicon can not form stable rings with itself

Electron density calculations by Nicholas Linn show that a Si_6H_6 molecule, the silicon analogue for benzene C_6H_6, is unstable. Figures 5.4 and 5.5 show the results of this calculation. You can see that the silicon ring is not stable enough.

5.5 Silicon combines reasonably well with other atoms

Why are silicon polymers not that stable? Silicon doesn't have a electronegativity even near carbon. It has an electronegativity of 1,7, while carbon has 2,5. The electronegativity of silicon is around the mean electronegativity of all elements. The bond length of silicon is also much higher, which doesn't exactly increase the stability: $224 \cdot 10^{-12}$ m for silicon against $77 \cdot 10^{-12}$ m for carbon.

Another problem is the silicon atom is too large to form so-called π-bonds, which are needed for stable polymers and rings.[3.2]

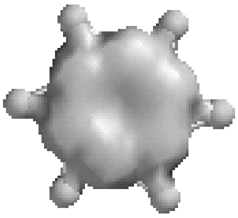

Figure 5.5 Silicon ring electron isodensity (by Nicholas Linn)[3.2]

5.6 Silicon dioxide is a solid

This is the largest problem for silicon-based life. Silicon dioxide (SiO_2) is a solid, better known as sand! The outcome of a process similar to oxidative phosphorylation is not a gas, but a solid. Imagine the problems of such an enormous amount of solid waste. Breathing becomes a real problem.

There's not much to stop the oxidization of silicon either: silicon has a large affinity for oxygen. We'll use this in section 6.1 for a alternative silicon polymer, but this means a silicon-based organism must either live on a oxygen-free planet or it must have a method to get rid of the solid silicon dioxide.

This adds another problem. Remember section 5.10, about the equilibrium between O_2 using heterotrophic organisms and CO_2 using autotrophic organisms? The fact that silicon dioxide is solid makes this a huge problem. It's much easier to use a gas like CO_2 than a rocky solid like SiO_2. An equilibrium becomes very difficult to maintain.

6 If silicon does not have the properties as described in section 3, does the lack of these properties pose an unsolvable problem for silicon as the basis of life? If not, what are possible solutions to this problem?

Without the ability to form long chains like carbon, silicon does not have the key properties required to form complex organic chemicals. This is a problem that can not really be solved to our satisfaction. We'll have to accept a less good alternative polymer to continue our discussion.

Figure 6.1 Double-bonded silicon polymer

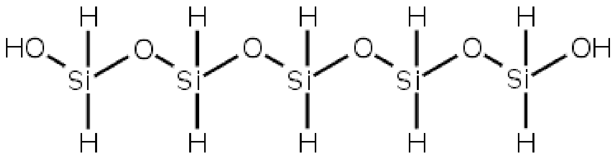

Figure 6.2 Silicon-oxygen hybrid polymer

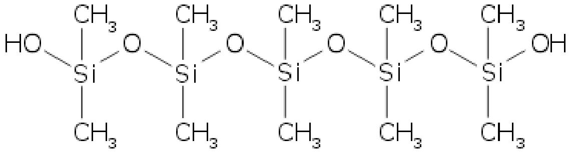

Figure 6.3 Silicon-oxygen-carbon hybrid polymer

6.1 Alternative stable silicon-polymers

Not all hope is lost though. There are several stable polymers with silicon. We'll discuss three of those polymers here: the double-bond polymer (figure 6.1), a silicon-oxygen hybrid (figure 6.2) and a silicon-oxygen-carbon hybrid (figure 6.3).

Silicon can form chains with a double covalent bond and this chain becomes stable as it bends in on itself, not allowing for the long formations we see in many organic chemicals. Also, since silicon requires a double bond to form a chain, it does not allow for the addition of as many other atoms on the base chain. This polymer is therefore completely unsuitable for any form of life.

One other stable alternative is actually being used today in, for example, cosmetic surgery. Yes, we're talking about silicone. This polymer uses the affinity silicon has for oxygen that gave us so many problems in 5.6. Silicone is a hybrid silicon-oxygen polymer with the general formula $Si_nO_{n+1}H_{2n+2}$. It is stable and special side groups can replace the hydrogen atoms.

The last alternative is proposed by Nicholas Linn and is a hybrid silicon-oxygen-carbon polymer. It is basically a silicone with the hydrogen's replaced with methyl groups (CH_3). The general formula is $Si_nC_{2n}O_{n+1}H_{6n+2}$.

We're going to assume our silicon-based life uses silicone (silicon-oxygen hybrid) as chemical backbone for its organic molecules.

6.2 The silicon-oxygen polymer still lacks a few of the properties described in section 3

The silicon-oxygen hybrid polymer is stable and can form long bonds. It can also have a lot of different extra chemical groups for more versatility. All the hydrogen atoms can be replaced with other groups. This supports the very complex molecules that are required for life. Rings can also be made with this polymer.

The silicon-oxygen hybrid also allows handedness, because the silicon atoms can still have four different groups attached to them. This is required for enzyme functions (see section 3.3).

There are two problems with the silicon-oxygen hybrid. This hybrid can not be made into a rigid shape. The double and triple required to do that are simply not possible because of the extra oxygen between every two silicon atoms. Another problem is that the molecules are a lot larger now, which may give problems in certain enzyme functions.

The second problem is that the solid SiO_2 problem isn't solved by this silicon-oxygen polymer (see section 5.6). It remains and it can't really be solved (see section 6.3).

6.3 The solid SiO_2 can not be solved without unsupported speculation

The fact that SiO_2 is solid (see section 5.6) is a huge problem for silicon-based life. There are only two ways to solve this problem and both are not pretty. In both cases we have to accept that silicon-based life has a process we know nothing about. We also don't know if such a process is even possible.

The first one is that silicon-based life occurs on a planet where there is no O_2 and SiO_2. Silicon has a high affinity for oxygen, so any atmospheric O_2 will pose a problem. The entire metabolism of these organisms has to be different. We don't know of any metabolism that does not use O_2 and CO_2. We don't even know if other metabolisms are possible. This is pure speculation.

The other way is that we accept that silicon-based life uses O_2 and SiO_2 and has SiO_2 as a waste product. It somehow gets rid of the solid SiO_2 and other silicon-based life is able to use the solid SiO_2 to form an equilibrium. We don't know if this is possible either.

7 What is the best environment for silicon-based life, keeping in mind section 6?

Of course life can not occur in every random place. It needs a certain environment to be formed in the first place and to stay alive after it has been formed. This section describes the best environment for silicon-based life similar to our life.

7.1 A temperature that isn't too low and isn't too high

We want the molecules that our silicon-based life is made of to be stable, but have enough energy for fast chemical reactions. The speed of the reactions depends, among other factors, on the temperature. Without fast chemical reactions, the life can not react to its environment quickly. At too high of a temperature, the molecules bump into each other so fast that the bonds get broken very easily. That's why we also need an upper limit. This limits the temperature in the area between about 50K and 1000K.

7.2 A liquid medium with a large temperature range

We need an environment with a liquid medium for the chemical reactions required for life to occur, if we want life similar to terrestrial life. This liquid has to be:

- A polar molecule, because we want all kinds of ions to be dissolved in our medium. Otherwise, the life can never get the metals it needs for certain chemical reactions.
- Ampholytic (both able to be an acid and an alkali), because this is required for the large range of chemical reactions needed for life.
- Generally not too reactive. We don't want our life to be killed by the medium it exists in?
- We also need a pretty large temperature range, >50K, because otherwise a small change in temperature (e.g. summer and winter) would kill all the life.

Since we also require hydrogen and oxygen, our best choice would be simple water, H_2O. For water to be liquid, we need a temperature between 273K and 373 K. It has all the four properties we need:

- It is polar, because there are two hydrogen atoms and two free electron pairs arranged in a tetrahedral shape around the oxygen atom.
- It is ampholytic, because H_2O can react to become an acid, H_3O^+, and a alkali, OH^-.
- It is generally not too reactive. Water does not react violently with your cells or otherwise you would not be alive right now.
- The temperature range is large enough, 100K to be exact.

Another possibility might be hydrogen fluoride, HF. This is liquid between 190K and 293K. It is not ampholytic (it is already acidic itself), but it has all the other properties.

7.3 An environment with a lot of silicon and the other life elements H, O, N, P and S

We want there to be a lot of silicon, right? Without silicon, silicon-based life is going to have a lot of trouble. The other elements are also needed a lot. Generally, we need a lot of diversity in the elements available. There is one problem though, if we have water, we have H, O, N, P and S, what prevents carbon-based life from being formed? Silicon-based life probably also needs traces of carbon, just like carbon-based life needs traces of silicon.

7.4 A layer that protects the silicon-based life from radiation

A lot of radiation hits the earth from space everyday. This radiation can kill us by causing mutations in our DNA. We don't get killed by it though. The atmosphere protects us from it. Silicon-based life need a protection layer as well. This can be either an atmosphere or a solid rock layer.

The most dangerous kind of radiation on planets similar to Earth is ultraviolet light. The rest of the radiation is usually already filtered out by a standard atmosphere, but ultraviolet light is takes very specific compounds to be filtered out. Ultraviolet light causes mutations in DNA, because it breaks molecular bonds. Ozone (O_3) protects from it and water also protects quite well against ultraviolet.[1,7]

7.5 A stable standard main-sequence star in a tranquil part of the galaxy

Life needs time to develop and a stable environment. That's why very big stars that burn up within a few hundred million years are not well suited for life. The best is a nice yellow standard main-sequence star, like our sun. It survives a few billion years without much fluctuations that can destroy life on the planets orbiting the star.

Some areas of galaxies are not very safe for life. The centres of most galaxies are thought to contain massive black holes. Areas with lots of red giants are dangerous because of the radiation caused by supernovae.

Whether gamma-ray bursts (GRBs) caused by hypernovae, black holes or other extreme astrophysical phenomena, we sure don't want our life to be in the proximity of such a GRB. It will probably sterilize the planet, because gamma rays are very energetic photons which break any molecular bond that gets into their way.[6.4]

8 Is the environment described in section 7 possible? If so, is it possible in our solar system?

Well, you're standing in that environment right now. Liquid water, protective atmosphere, the right temperature and plenty of silicon and the other elements required for life. Our sun is a great example of a standard main-sequence star with a safe part of the galaxy. Calculations indicate that in most spiral galaxies like the Milky-way there is a ring-shaped zone that is the most safe for life.[6.3]

Silicon is 25.7% of the earth's crust.[5.1] However, there is no silicon-based life on earth now, only carbon-based life. The problems posed by solid SiO_2 and the problems with silicon polymers apparently could not be solved on earth. It is also possible that silicon-based life has formed, but that the carbon-based life was simply a too powerful concurrent. Maybe silicon-based life is possible on earth-like planets, if it gets a chance. This is only speculation though. There is no evidence that there has ever been silicon-based life anywhere.

Another environment that might have supported silicon-based life or maybe still has silicon-based life is Mars. There are indications that there was once liquid water and there's enough silicon for life to form.[6.2] Maybe future missions will find the remains of silicon-based life, although the chance that this happens is in our opinion very small.

There is enough silicon in the universe for silicon-based life to be a real possibility. Silicon is 0.003% of the atoms in the universe. Carbon is 0.05% of the atoms in the universe.[5.1] We can measure this by looking at spectrographs of the light that reaches us. The predictions made by tested models of stars give similar results to these measurements. There is generally more silicon in areas where there have been more generations of stars. Silicon, like carbon, is formed by every star in the last phase of its life. All elements before iron are always created. Since iron is element 26 and silicon is 14, silicon is always formed. Generally the rule is: the more stars there have been in a part of space, the more silicon atoms are present.[5.2]

9 Is there a possibility of silicon-based life that is totally different from life as we know it?

Any silicon-based life would have to be significantly different from life as we know it. There is no basis for such life and therefore resides in the realm of speculation. Our finds in this report indicate that if we look for silicon-based life, we should look for organisms totally different from terrestrial organisms and we should look for these organisms in strange, like asteroids without atmosphere or huge gas giants like Jupiter.

9.1 Life that uses a different phosphorylation catalyst

In section 6.3 we said the problem with solid SiO_2 can not be solved without unsupported speculation and since this is the section for unsupported speculation, we will discuss some solutions to this problem here.

A silicon-based organism might live on a planet without oxygen. There is no good reason why organism could not use another gas as a phosphorylation catalyst, like hydrogen, nitrogen or other reactive gasses. It is also possible that methane, CH_4 might replace phosphor in the metabolic pathway. This would allow totally different metabolisms which might not have the problem of producing a lot of solid waste.

Some terrestrial organisms use S_2 and H_2S instead of O_2 and H_2O in the photosynthesis reaction. The problem with the CO_2-equivalent SiO_2 still remains, because the reaction still uses CO_2.

9.2 Glass-like organisms

A major component of glass is silicon. It might be possible that an organism based on glass exists. An organism like that may get its energy from solar-cell like cells. Zeolites[4.5], microporous minerals based on silicon, aluminium and oxygen, might play a role in these organisms.

9.3 Artificial intelligence

Although the development of computers seems to be going in the direction of computers based on organic components or new carbon chemistry, artificial intelligence in current computers can be referred to as silicon-based life. The basic chemicals of computers are at the moment silicon and copper. Artificial intelligence doesn't have any of the problems silicon-based life similar to terrestrial life has. It would work with electricity made with solar-cells or nuclear energy instead of energy stored in biological molecules.

It would be strange to find an alien artificial intelligence living all by itself, because artificial intelligence can, as far as we know, only be created by other intelligent beings. Silicon and copper pure enough for chips is not found in nature. We don't know of any natural process to make it pure enough, so it is reasonable to assume that all artificial intelligence is created by other intelligent beings.

10 Conclusion: Is silicon-based life similar to terrestrial life possible?

Silicon-based life similar to terrestrial life is probably not possible. In a naive view of chemistry it may seem possible, but all the evidence points in the other direction. The problems with solid SiO_2 and the fact that silicon has problems forming long stable chains make silicon-based life similar to terrestrial life impossible. Totally different life may be possible though (see chapter 9). That chapter, however, is only speculation and there is no indication that such organisms exist.

11 Sources and links with further information

This section contains sources used for the article and links with further information on subjects touched in this article.

11.1 Chemical drawings

All chemicals drawings done by Amantine in MDL ISISdraw, unless stated otherwise in the comment beneath the figure. There is a free version of this program available at http://www.mdli.com/.

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11.3 Chemical basis of life

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11.4 Silicon-based life

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11.5 Silicon chemistry

4.1	"WebElements: Silicon", http://www.webelements.com/webelements/elements/text/Si/key.html
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4.3	"Silicones", University of Southern Mississippi, http://www.psrc.usm.edu/macrog/silicone.htm
4.4	"Silicon", University of North Carolina at Pembroke, http://www.uncp.edu/home/mcclurem/ptable/silicon/si.htm
4.5	"Zeolites", http://www.bza.org/zeolites.html

11.6 Abundancy of silicon

5.1	"WebElements: Silicon geological information", http://www.webelements.com/webelements/elements/text/Si/geol.html
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11.7 Planet information

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11.8 History of silicon-based life in science fiction and science

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