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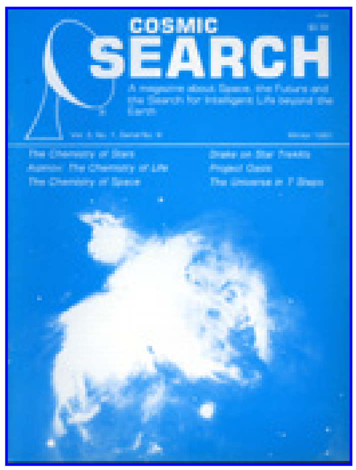

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Not as We Know it
The Chemistry of Life

By: Isaac Asimov

Even unpleasant experiences can be inspiring.

Isaac Asimov

For instance, my children once conned me into taking them to a monster-movie they had seen advertised on TV. "It's *science fiction*," they explained. They don't exactly know what science fiction is, but they have gathered it's something daddy writes, so the argument is considered very powerful.

I tried to explain that it wasn't science fiction by my definition, but although I had logic on my side, they had decibels on theirs.

So I joined a two-block line consisting of every kid for miles around with an occasional grown-up who spent his time miserably pretending he was waiting for a bus and would leave momentarily. It was a typical early spring day in New England — nasty drizzle whipped into needle-spray by a howling east wind — and we inched slowly forward.

Finally, when we were within six feet of the ticket-sellers and I, personally, within six inches of pneumonia, my guardian angel smiled and I had my narrow escape. They hung up the SOLD OUT sign.

I said, with a merry laugh, "Oh, what a dirty shame," and drove my howling indignant children home. Anyway, it got me to thinking about the lack of imagination in movieland's monsters. Their only attributes are their bigness and destructiveness. They include big apes, big octopuses (or is the word "octopodes"?), big eagles, big spiders, big amoebae. In a way, that is all Hollywood needs, I suppose. This alone suffices to drag in huge crowds of vociferous human larvae, for to be big and destructive is the secret dream of every red-blooded little boy and girl in the world.

What, however, is mere size to the true *aficionado*? What we want is real variety. When the cautious astronomer speaks of life on other worlds with the qualification "life-as-we-know-it," we become impatient. What about life-not-as-we-know-it?

Well, that's what I want to discuss.

To begin with, we have to decide what life-as-we-know-it, means. Certainly life-as-we-know-it is infinitely various. It flies, runs, leaps, crawls, walks, hops, swims, and just sits. It is green, red, yellow, pink, dead white and vari-colored. It glows and does not glow, eats and does not eat. It is boned, shelled, plated and soft; has limbs, tentacles or no appendages at all; it is hairy, scaly, feathery, leafy, spiny and bare.

If we're going to lump it all as life-as-we-know-it, we'll have to find out something it all has in common. We might say it is all composed of cells, except that this is not so. The virus, an important life form to anyone who has ever had a cold, is not.

So we must strike beyond physiology and reach into chemistry, saying that all life is made up of a directing set of nucleic acid molecules which controls chemical reactions through the agency of proteins working in a watery medium.

There is more, almost infinitely more, to the details of life, but I am trying to strip it to a basic minimum. For life-as-we-know-it, water is the indispensable background against which the drama is played out, and nucleic acids and proteins are the featured players.

Hence any scientist, in evaluating the life possibilities on any particular world, instantly dismisses said world if it lacks water; or if it possesses water outside the liquid range, in the form of ice only or of steam only.

(You might wonder, by the way, why I don't include oxygen as a basic essential. I don't because it isn't. To be sure, it is the substance most characteristically involved in the mechanics by which most life forms evolve energy, but it is not invariably involved. There are tissues in our body that can live temporarily in the absence of molecular oxygen, and there are microorganisms that can live indefinitely in the absence of oxygen. Life on earth almost certainly developed in an oxygen-free atmosphere, and even today there are microorganisms that can live only in the absence of oxygen. No known life form on earth, however, can live in the complete absence of water, or fails to contain both protein and nucleic acid.)

In order to discuss life-not-as-we-know-it, let's change either the background or the feature players. Background first!

Water is an amazing substance with a whole set of unusual properties which are ideal for life-as-we-know-it. So well fitted for life is it, in fact, that some people have seen in the nature of water a sure sign of Divine providence. This, however, is a false argument, since life has evolved to fit the watery medium in which it developed. Life fits water, rather than the reverse.

Can we imagine life evolving to fit some other liquid, then, one perhaps not too different from water? The obvious candidate is ammonia.

Ammonia is very like water in almost all ways. Whereas the water molecule is made up of an oxygen atom and two hydrogen atoms (H_2O) for an atomic weight of 18, the ammonia molecule is made up of a nitrogen atom and three hydrogen atoms (NH_3) for an atomic weight of 17. Liquid ammonia has almost as high a heat of evaporation, almost as high a versatility as a solvent, almost as high a tendency to liberate a hydrogen ion.

In fact, chemists have studied reactions proceeding in liquid ammonia and have found them to be quite analogous to those proceeding in water, so that an "Ammonia chemistry" has been worked out in considerable detail.

Ammonia as a background to life is therefore quite conceivable — but not on earth. The temperatures on earth are such that ammonia exists as a gas. Its boiling point at atmospheric pressure is -33.4° C. (-28° F.) and its freezing point is -77.7° C. (-108° F.).

But other planets?

In 1931, the spectroscope revealed that the atmosphere of Jupiter, and, to a lesser extent, of Saturn, was loaded with ammonia. The notion arose at once of Jupiter being covered by huge ammonia oceans.

To be sure, Jupiter may have a temperature not higher than -100° C. (-148° F.), so that you might suppose the mass of ammonia upon it to exist as a solid, with atmospheric vapor in equilibrium. Too bad. If Jupiter were closer to the sun ...

But wait! The boiling point I have given for ammonia is at atmospheric pressure — earth's atmosphere. At higher pressures, the boiling point would rise, and if Jupiter's atmosphere is dense enough and deep enough, ammonia oceans might be possible after all.

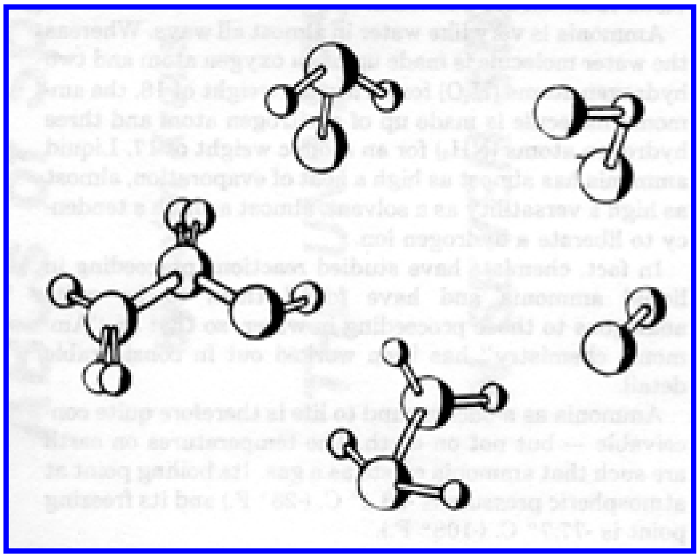
An objection that might, however, be raised against the whole concept of an ammonia background for life, rests on the fact that living organisms are made up of unstable compounds that react quickly, subtly and variously. The proteins that are so characteristic of life-as-we-know-it must consequently be on the edge of instability. A slight rise in temperature and they break down.

A drop in temperature, on the other hand, might make protein molecules too stable. At temperatures near the freezing point of water, many forms of non-warm-blooded life become sluggish indeed. In an ammonia environment with temperatures that are a hundred or so Centigrade degrees lower than the freezing point of water, would not chemical reactions become too slow to support life?

The answer is twofold. In the first place, why is "slow" to be considered "too slow?" Why might there not be forms of life that live at slow motion compared to ourselves? Plants do.

A second and less trivial answer is that the protein structure of developing life adapted itself to the temperature by which it was surrounded. Had it adapted itself over the space of a billion years to liquid ammonia temperatures, protein structures might have been evolved that would be far too unstable to exist for more than a few minutes at liquid water temperatures, but are just stable enough to exist conveniently at liquid ammonia temperatures. These new forms would be just stable enough and unstable enough at low temperatures to support fast-moving forms of life.

Nor need we be concerned over the fact that we can't imagine what those structures might be. Suppose we were creatures who lived constantly at a temperature of a dull red heat (naturally with a chemistry fundamentally different from that we now have). Could we under those circumstances know anything about earth-type proteins? Could we refrigerate vessels to a mere 25° C., form proteins and study them? Would we ever dream of doing so, unless we first discovered life forms utilizing them?



Anything else besides ammonia now?

Well, the truly common elements of the universe are hydrogen, helium, carbon, nitrogen, oxygen and neon. We eliminate helium and neon because they are completely inert and take part in no reactions. In the presence of a vast preponderance of hydrogen throughout the universe, carbon, nitrogen and oxygen would exist as hydrogenated compounds. In the case of oxygen, that would be water (H_2O), and in the case of nitrogen, that would be ammonia (NH_3). Both of these have been considered. That leaves carbon, which, when hydrogenated, forms methane (CH_4).There is methane in the atmosphere of Jupiter and Saturn, along with ammonia; and, in the still more distant planets of Uranus and Neptune, methane is predominant, as ammonia is frozen out. This is because methane is liquid over a temperature range still lower than that of ammonia. It boils at -161.6° C. (-259° F.) and freezes at -182.6° C. (-297° F.) at atmospheric pressure.

Could we then consider methane as a possible background to life with the feature players being still more unstable forms of protein? Unfortunately, it's not that simple.

Ammonia and water are both polar compounds; that is, the electric charges in their molecules are unsymmetrically distributed. The electric charges in the methane molecule are symmetrically distributed, on the other hand, so it is a non-polar compound.

Now, it so happens that a polar liquid will tend to dissolve polar substances but not nonpolar substances, while a nonpolar liquid will tend to dissolve nonpolar substances but not polar ones.

Thus water, which is polar, will dissolve salt and sugar, which are also polar, but will not dissolve fats or oils (lumped together as "lipids" by chemists), which are nonpolar. Hence the proverbial expression, "Oil and water do not mix."

On the other hand, methane, a nonpolar compound, will dissolve lipids but will not dissolve salt or sugar. Proteins and nucleic acids are polar compounds and will not dissolve in methane. In fact, it is difficult to conceive of any structure that would jibe with our notions of what a protein or nucleic acid ought to be that would dissolve in methane.

If we are to consider methane, then, as a background for life, we must change the feature players.

To do so, let's take a look at protein and nucleic acid and ask ourselves what it is about them that makes them essential for life.

Well, for one thing, they are giant molecules, capable of almost infinite variety in structure and therefore potentially possessed of the versatility required as the basis of an almost infinitely varying life.

Is there no other form of molecule that can be as large and complex as proteins and nucleic acids and that can be nonpolar, hence soluble in methane, as well? The most common nonpolar compounds associated with life are the lipids, so we might ask if it is possible for there to exist lipids of giant molecular size.

Such giant lipid molecules are not only possible; they actually exist. Brain tissue, in particular, contains giant lipid molecules of complex structure (and of unknown function). There are large "lipoproteins" and "proteolipids" here and there which are made up of both lipid portions and protein portions combined in a single large molecule. Man is but scratching the surface of lipid chemistry; the potentialities of the nonpolar molecule are greater than we have, until recent decades, realized.

Remember, too, that the biochemical evolution of earth's life has centered about the polar medium of water. Had life developed in a nonpolar medium, such as that of methane, the same evolutionary forces might have endlessly proliferated lipid molecules into complex and delicately unstable forms that might then perform the functions we ordinarily associate with proteins and nucleic acids.

Working still further down on the temperature scale, we encounter the only common substances with a liquid range at temperatures below that of liquid methane. These are hydrogen, helium, and neon. Again, eliminating helium and neon, we are left with hydrogen, the most common substance of all. (Some astronomers think that Jupiter may be four-fifths hydrogen, with the rest mostly helium — in which case good-by ammonia oceans after all.)

Hydrogen is liquid between temperatures of -253° C. (-423° F.) and -259° C. (-434° F.), and no amount of pressure will raise its boiling point higher than -240° C. (-400° F.). This range is only twenty to thirty Centigrade degrees over absolute zero, so that hydrogen forms a conceivable background for the coldest level of life. Hydrogen is nonpolar, and again it would be some sort of lipid that would represent the featured player.

So far the entire discussion has turned on planets colder than the earth. What about planets warmer?

To begin with, we must recognize that there is a sharp chemical division among planets. Three types exist in the solar system and presumably in the universe as a whole.

On cold planets, molecular movements are slow, and even hydrogen and helium (the lightest and therefore the nimblest of all substances) are slow-moving enough to be retained by a planet in the process of formation. Since hydrogen and helium together make up almost all of matter; this means that a large planet would be formed. Jupiter, Saturn, Uranus and Neptune are the examples familiar to us.

On warmer planets, hydrogen and helium move quickly enough to escape. The more complex atoms, mere impurities in the overriding ocean of hydrogen and helium, are sufficient to form only small planets. The chief hydrogenated compound left behind is water, which is the highest-boiling compound of the methane-ammonia-water trio and which, besides, is most apt to form tight complexes with the silicates making up the solid crust of the planet.

Worlds like Mars, earth, and Venus result. Here, ammonia and methane forms of life are impossible. Firstly, the temperatures are high enough to keep those compounds gaseous. Secondly, even if such planets went through a super-ice-age, long aeons after formation, in which temperatures dropped low enough to liquefy ammonia or methane, that would not help. There would be no ammonia or methane in quantities sufficient to support a world-girdling life form.

Imagine, next a world still warmer than our medium trio: a world hot enough to lose even water. The familiar example is Mercury. It is a solid body of rock with little, if anything, in the way of hydrogen or hydrogen-containing compounds.

Does this eliminate any conceivable form of life that we can pin down to existing chemical mechanisms?

Not necessarily.

There are nonhydrogenous liquids, with ranges of temperature higher than that of water. The most common of these, on a cosmic scale, has a liquid range from 113° C. (235° F.) to 445° C. (833° F.); this would fit nicely into the temperature of Mercury's sunside.

But what kind of featured players could be expected against such a background?

So far all the complex molecular structures we have considered have been ordinary organic molecules; giant molecules, that is, made up chiefly of carbon and hydrogen, with oxygen and nitrogen as major "impurities" and sulfur and phosphorus as minor ones. The carbon and hydrogen alone would make up a nonpolar molecule; the oxygen and nitrogen add the polar qualities.

In a watery background (oxygen-hydrogen) one would expect the oxygen atoms of tissue components to outnumber the nitrogen atoms, and on earth this is actually so. Against an ammonia background, I imagine nitrogen atoms would heavily outnumber oxygen atoms. The two subspecies of proteins and nucleic acids that result might be differentiated by an O or an N in parentheses, indicating which species of atom was the more numerous.

The lipids, featured against the methane and hydrogen backgrounds, are poor in both oxygen and nitrogen and are almost entirely carbon and hydrogen, which is why they are nonpolar.

But in a hot world like Mercury, none of these types of compounds could exist. No organic compound of the types most familiar to us, except for the very simplest, could long survive liquid sulfur temperatures. In fact, earthly proteins could not survive a temperature of 60° C. for more than a few minutes.

How then to stabilize organic compounds? The first thought might be to substitute some other element for hydrogen, since hydrogen would, in any case, be in extremely short supply on hot worlds.

So let's consider hydrogen. The hydrogen atom is the smallest of all atoms and it can be squeezed into a molecular structure in places where other atoms will not fit. Any carbon chain, however intricate, can be plastered round and about with small hydrogen atoms to form "hydrocarbons." Any other atom, but one, would be too large.

And which is the "but one?" Well, an atom with chemical properties resembling those of hydrogen (at least as far as the capacity for taking part in particular molecular combinations is concerned) and one which is almost as small as the hydrogen atom, is that of fluorine. Unfortunately, fluorine is so active that chemists have always found it hard to deal with and have naturally turned to the investigation of tamer atomic species.

This changed during World War II. It was then necessary to work with uranium hexafluoride, for that was the only method of getting uranium into a compound that could be made gaseous without trouble. Uranium research had to continue (you know why), so fluorine had to be worked with, willy-nilly.

As a result, a whole group of "fluorocarbons," complex molecules made up of carbon and fluorine rather than carbon and hydrogen, were developed, and the basis laid for a kind of fluoro-organic chemistry.

To be sure, fluorocarbons are far more inert than the corresponding hydrocarbons (in fact, their peculiar value to industry lies in their inertness) and they do not seem to be in the least adaptable to the flexibility and versatility required by life forms.

However, the fluorocarbons so far developed are analogous to polyethylene or polystyrene among the hydro-organics. If we were to judge the potentialities of hydro-organics only from polyethylene, I doubt that we would easily conceive of proteins.

No one has yet, as far as I know, dealt with the problem of fluoroproteins or has even thought of dealing with it — but why not consider it? We can be quite certain that they would not be as active as ordinary proteins at ordinary temperatures. But on a Mercury-type planet, they would be at higher temperatures, and where hydro-organics would be destroyed altogether, fluoro-organcs might well become just active enough to support life, particularly the fluoro-organics that life forms are likely to develop.

Such fluoro-organic-in-sulfur life depends, of course, on the assumption that on hot planets, fuorine, carbon and sulfur would be present in enough quantities to make reasonably probable the development of life forms by random reaction over the life of a solar system. Each of these elements is moderately common in the universe, so the assumption is not an altogether bad one. But, just to be on the safe side, let's consider possible alternatives.

Suppose we abandon carbon as the major component of the giant molecules of life. Are there any other elements which have the almost unique property of carbon — that of being able to form long atomic chains and rings — so that giant molecules reflecting life's versatility can exist?

The atoms that come nearest to carbon in this respect are boron and silicon, boron lying just to the left of carbon on the periodic table (as usually presented) and silicon just beneath it. Of the two, however, boron is a rather rare element. Its participation in random reactions to produce life would be at so slow a rate, because of its low concentration in the planetary crust, that a boron-based life formed within a mere five billion years is of vanishingly small probability.

That leaves us with silicon, and there, at least, we are on firm ground. Mercury, or any hot planet, may be short on carbon, hydrogen and fluorine, but it must be loaded with silicon and oxygen, for these are the major components of rocks. A hot planet which begins by lacking silicon and oxygen as well, just couldn't exist because there would be nothing left in enough quantity to make up more than a scattering of nickel-iron meteorites.

Silicon can form compounds analogous to the carbon chains. Hydrogen atoms tied to a silicon chain, rather than to a carbon chain, form the "silanes." Unfortunately, the silanes are less stable than the corresponding hydrocarbons and are even less likely to exist at high temperatures in the complex arrangements required of molecules making up living tissue.

Yet it remains a fact that silicon does indeed form complex chains in rocks and that those chains can easily withstand temperatures up to white heat. Here, however, we are not dealing with chains composed of silicon atoms only (Si-Si-Si-Si-Si) but of chains of silicon atoms alternating with oxygen atoms (Si-O-Si-O-Si).

It so happens that each silicon atom can latch on to four oxygen atoms, so you must imagine oxygen atoms attached to each silicon atom above and below, with these oxygen atoms being attached to other silicon atoms also, and so on. The result is a three-dimensional network, and an extremely stable one.

But once you begin with a silicon-oxygen chain, what if the silicon atom's capacity for hooking on to two additional atoms is filled not by more oxygen atoms but by carbon atoms, with, of course, hydrogen atoms attached? Such hybrid molecules, both silicon- and carbon-based, are the "silicones." These, too, have been developed chiefly during World War II and since, and are remarkable for their great stability and inertness.

Again, given greater complexity and high temperature, silicones might exhibit the activity and versatility necessary for life. Another possibility: Perhaps silicones may exist in which the carbon groups have fluorine atoms attached, rather than hydrogen atoms. Fluorosilicones would be the logical name for these, though, as far as I know — and I stand very ready to be corrected — none such have yet been studied.

Might there possibly be silicone or fluorosilicone life forms in which simple forms of this class of compound (which can remain liquid up to high temperatures) might be the background of life and complex forms the principal character?

There, then, is my list of life chemistries, spanning the temperature range from near red heat down to near absolute zero:

1. fluorosilicone in fluorosilicone
2. fluorocarbon in sulfur
3.*nucleic acid/protein (O) in water
4. nucleic acid/protein (N) in ammonia
5. lipid in methane
6. lipid in hydrogen

Of this half dozen, the third only is life-as-we-know-it. Lest you miss it, I've marked it with an asterisk.

This, of course, does not exhaust the imagination, for science-fiction writers have postulated metal beings living on nuclear energy, vaporous beings living in gases, energy beings living in stars, mental beings living in space, indescribable beings living in hyperspace, and so on.

It does, however, seem to include the most likely forms that life can take as a purely chemical phenomenon based on the common atoms of the universe.

Thus, when we go out into space there may be more to meet us than we expect. I would look forward not only to our extra-terrestrial brothers who share life-as-we-know-it. I would hope also for an occasional cousin among the life-not-as-we-know-it possibilities.

In fact, I think we ought to prefer our cousins. Competition may be keen, even overkeen, with our brothers, for we may well grasp at one another's planets; but there need only be friendship with our hot-world and cold-world cousins, for we dovetail neatly. Each stellar system might pleasantly support all the varities, each on its own planet, and each planet useless to and undesired by any other variety.

How easy it would be to observe the Tenth Commandment then!

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Isaac Asimov

Isaac Asimov is a scientist, a teacher and the prolific author of 225 books to date. Covering a great variety of topics, they range, to mention just a few, from "Biochemistry and Human Metabolism" a textbook (1957), "Races and People" (1955), "The Human Body" (1963), "The Genetic Code" (1963), "Intelligent Man's Guide to Science" (1960), "Short History of Chemistry" (1965), "Quick and Easy Math" (1964), "Great Ideas of Science" (1969) and "Our World in Space" (1974) to "Asimov's Guide to the Bible" in 2 volumes (1968-1969), "Asimov's Guide to Shakesspeare" in 2 volumes (1970), Asimov's Annotated Paradise Lost" (1974) and "Isaac Asimov's Treasury of Humor" (1971). His accompanying article is from his book "View from a Height" (1963).

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