

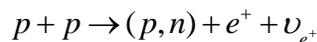
The elements of life

The fundamental transition from monomers to polymers must be energy driven and the energy required is of a special kind, ATP. This energy has to be synthesized by the cell. The metabolic pathways are structured around this requirement with energy pathways forming the core of metabolism. Electron current, whether generated by light through the primary steps of photosynthesis or by oxidation of glucose in non-photosynthetic organisms, either yields ATP directly by chemical coupling during glycolysis or through the intermediacy of proton currents across a membrane and then through membrane bound ATPase complexes. Why do these processes occur at all? Why are the elements that are central to these processes the ones that are involved? Is the chemical nature of life on Earth peculiar to this planet or is it representative of how the situation must be anywhere in the Universe? Life is made from what is available. What is available is made in stars, and eventually can be found in the matter in planets revolving around suns.

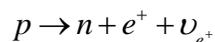
Stellar nucleosynthesis

In the Big Bang model of the evolution of the universe, an extremely dense and hot *ylem* expands and cools, giving rise to stars by collapse of locally supercritical masses of mixtures of hydrogen and helium (~25% helium). During collapse, half of the gravitational potential energy of a supercritical mass is converted into kinetic energy, causing the gas temperature to rise; the other half is radiated into space. As the temperature rises, ionization strips electrons from hydrogen atoms, leaving protons.

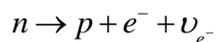
When $T \sim 10^7$ K and $\rho \sim 10^2$ g/cm³ (100 x ρ_{water} at one atmosphere pressure and 0 °C) the transition to nuclear energy generation begins with the proton-proton reaction. Below this T the protons repel each other coulombically. If T is high enough, however, collisions bring protons close enough together so that the short ranged strong nuclear force can act. It is strongly attractive. The reaction is



where p denotes a proton, n denotes a neutron, e^+ denotes a positron, ν_{e^+} denotes a positron neutrino, and (p, n) denotes a deuteron. In this reaction, one proton undergoes β^+ -decay. A free proton cannot do this, i.e.

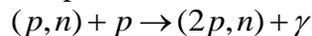


is impossible for a free p . However,

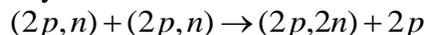


is possible since the mass of a neutron is 1839 electron masses and that of a proton is only 1836 electron masses.

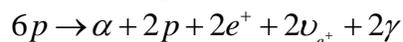
Inside the newly formed star, hot protons surround the deuterons leading to



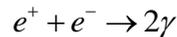
where $(2p, n)$ is a ³He nucleus and γ is a gamma ray photon. $(2p, n)$ does not combine with p 's, which instead elastically scatter. Deuterons used to form ³He become too rare to combine appreciably with ³He. Consequently ³He accumulates until hot ³He collisions take place



in which $(2p, 2n)$ denotes a ⁴He nucleus or α particle. Overall, the process is



The e^+ 's eventually annihilate with e^- 's previously formed by ionization

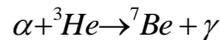


The neutrinos escape into interstellar space.

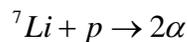
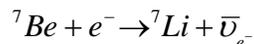
The mass of an α is 99.34% the mass of four p's. Thus Einstein's mass energy, mc^2 , is released by nuclear fusion. In the Sun, 600 million tons of p's fuse every second to form 596 million tons of α 's; 4 million tons of matter turn into energy. This is equivalent to 60 million billion kilowatt-hours of energy every second, 6×10^{16} kW-hr/s. Nuclear fusion will keep the Sun burning at this rate for several billion years; gravitational energy alone could produce energy at this rate for only 50 million years.

Addition of another nucleon to an α particle leads to unstable products such as ${}^5\text{Li}$ ($p + \alpha$) and ${}^5\text{He}$ ($n + \alpha$) that have lifetimes of 10^{-21} s. As the star ages, p's convert to α 's and this creates a nonhomogeneous interior. In the star's core, where T and ρ are highest, α particles accumulate at the expense of p's. The α 's of the core mix only very slowly with the star's outer envelope of p's. The core of α 's grows in size, but at its present T (10^7 K) the electrostatic repulsion, that is greater between the $2+$ α 's than between the $1+$ p's, inhibits α - α nuclear fusion reactions. Much higher T is required for α - α fusion. Nevertheless, at $T \sim 10^7$ K the nuclei of ${}^3\text{He}$ and ${}^4\text{He}$ can combine to make ${}^7\text{Be}$, beryllium, that can react in the star to form other isotopes of lithium, boron and beryllium. Such reactions explain how the nuclei of elements lighter than carbon come into being. They also produce more α 's.

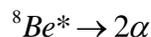
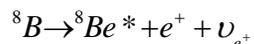
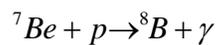
In the formation of more α 's just alluded to, an α serves as a catalyst for its own formation. This is called *autocatalysis*. Autocatalysis is the epitome of cellular life (cf. glycolysis and the Calvin cycle) and it has its first precursor at this stage. As shown above, two α 's can combine to form a ${}^4\text{He}$ nucleus. An α and a ${}^3\text{He}$ can react to form beryllium



There are now two different fates for this ${}^7\text{Be}$. Either



or



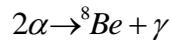
The outcomes are the same, two α 's. The initial α used to generate ${}^7\text{Be}$ is regenerated along with another. Thus it has served as an autocatalyst.

The star now has a core of hot, but non-reactive, α 's and an outer envelope of protons (ionized H atoms), electrons, and H_2 . A thin spherical shell surrounding the α core is the region in which nuclear fusion and energy generation continue. As a consequence, this region is the hottest ($\sim 3 \times 10^7$ K) and the most luminous.

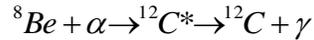
The origin of carbon

Gravitational contraction of the core α 's cause them to heat up because of conservation of energy during collapse. This leads to a great expansion of the surrounding envelope that can radiate at a lower temperature as it gets bigger. The surface reddens in color and the result is

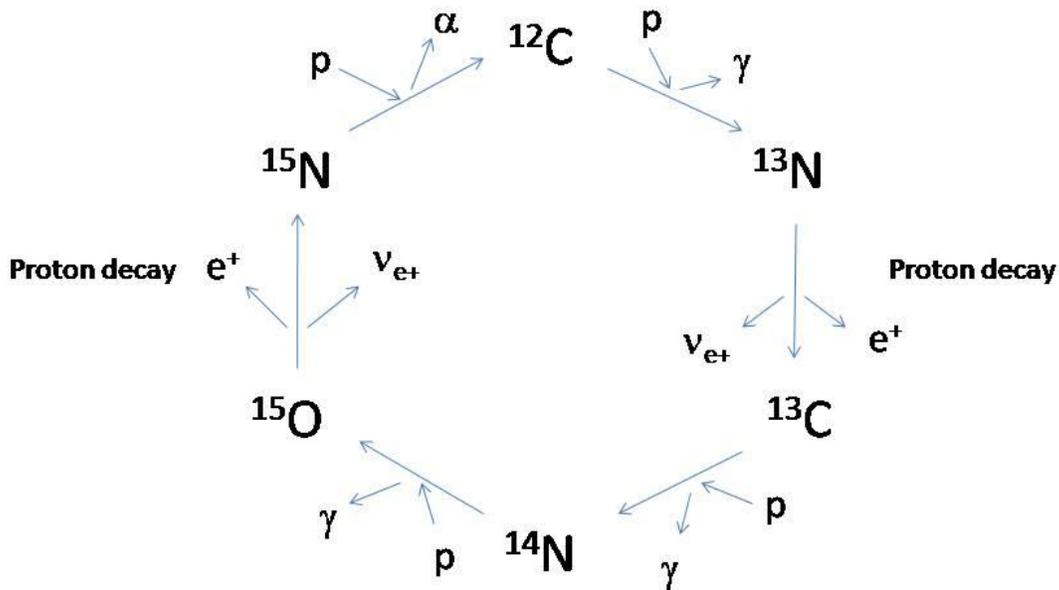
called a *red giant*. When the core α 's reach 10^8 K and $\rho = 10^5$ g/cm³, the coulombic repulsion of the α 's is overcome and they react and fuse. However, the natural product of the α fusion, the beryllium nucleus ${}^8\text{Be}$, has a lifetime of only 10^{-16} s before it reverts to α 's. The fusion reaction



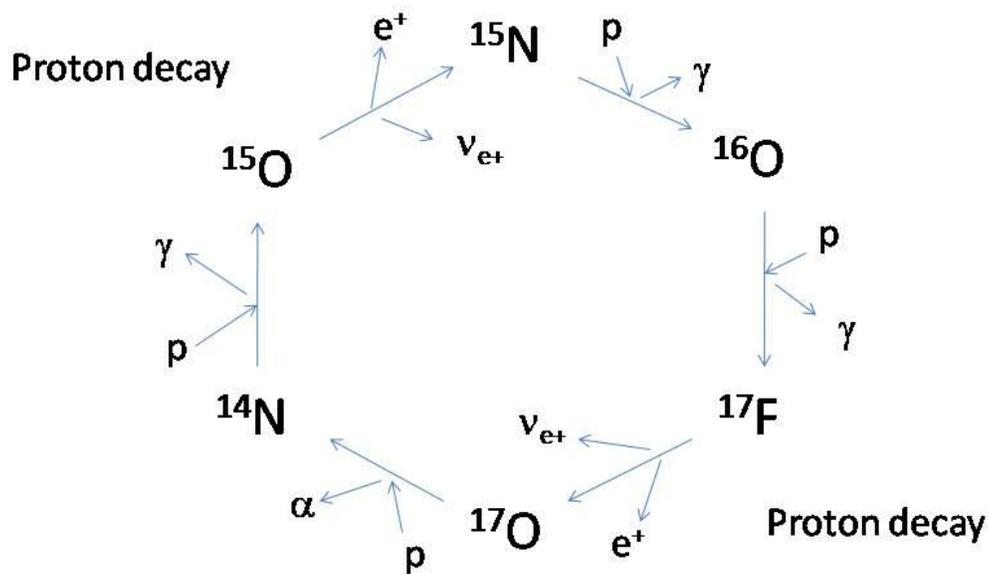
does not produce ${}^8\text{Be}$ fast enough to dominate the decay of ${}^8\text{Be}$ into α 's. Nevertheless, a small amount does get produced in equilibrium. Salpeter and Hoyle predicted and experimentally confirmed an alternative outcome



where ${}^{12}\text{C}^*$ is an excited state of the carbon nucleus that subsequently relaxes to a ground state carbon nucleus and emits a photon. Further collapse of the core α 's leads to $T = 10^9$ K. This is hot enough for the CN cycle to operate



In this cycle, C acts as a catalyst for the fusion of four p's into one α . For approximately every 2000 of these events, an alternative pathway converts ${}^{15}\text{N}$ into ${}^{14}\text{N}$ plus an α through ${}^{16}\text{O}$ and ${}^{17}\text{O}$ intermediates



Both ^{15}O of the CN cycle and ^{17}O are radioactive and decay rapidly, but ^{16}O is a stable intermediate that grows in abundance.

At $T = 10^9$ K, ^{12}C and ^{16}O nuclei react with α 's to produce the nuclei of ^{20}Ne , ^{24}Mg , ^{28}Si and ^{32}S as the most stable products. Reactions involving p's (similar to the CNO cycles above) lead to intermediate nuclei of fluorine, sodium, aluminum and phosphorous (F, Na, Al, P). Reactions among larger nuclei require higher T because of the greater charges and greater coulombic repulsion. However, at 3×10^9 K, the process of photodisintegration begins to contribute to these reactions. The absorption of light by ^{28}Si nuclei causes them to disintegrate into 7 α 's each ($\gamma + ^{28}\text{Si} \rightarrow 7\alpha$). Sometimes a ^{28}Si will capture 7 of these α 's to produce the nickel nucleus, ^{56}Ni ($^{28}\text{Si} + 7\alpha \rightarrow ^{56}\text{Ni}$). ^{56}Ni decays into radioactive ^{56}Co that in turn decays into the stable nucleus ^{56}Fe . Other nuclei are produced by similar means. This explains the origin of the first 30 elements of the periodic table.

Periodic Table

H								He
Li	Be		B	C	N	O	F	Ne
Na	Mg		Al	Si	P	S	Cl	Ar
K	Ca	ScTiVCrMn	Fe	CoNiCuZn				

Clearly, nuclei (in red) that are integer multiples of α 's should dominate the abundances of nearby nuclei in the periodic table that are not of this form. This is shown in the Universe abundance table below.

ELEMENT (NAME)	ATOMIC NUMBER	PARTS PER BILLION (BY WEIGHT)	FREQUENCY (BY ATOM)
Hydrogen	1	750,000,000	750,000,000
Helium	2	230,000,000	58,000,000
Oxygen	8	10,000,000	630,000
Carbon	6	5,000,000	420,000
Nitrogen	7	1,000,000	71,000
Neon	10	1,300,000	65,000
Silicon	14	700,000	25,000
Magnesium	12	600,000	25,000
Iron	26	1,100,000	20,000
Sulphur	16	500,000	16,000
Argon	18	200,000	5,000
Aluminum	13	50,000	1,900
Calcium	20	70,000	1,800
Nickel	28	60,000	1,000
Sodium	11	20,000	870
Chromium	24	15,000	290
Phosphorous	15	7,000	230
Manganese	25	8,000	150
Potassium	19	3,000	75

Titanium	22	3,000	63
Cobalt	27	3,000	51
Chlorine	17	1,000	29
Fluorine	9	400	21
Vanadium	23	1,000	20
Zinc	30	300	4.6
Copper	29	60	0.93
Lithium	3	6	0.87
Scandium	21	30	0.66
Beryllium	4	2	0.22
Boron	5	2	0.18

Notice in particular that N is the first element in the table not having an α -multiple nucleus. H, O, C, and N make up 4 out of the top 5 (He is the fifth). Among many other features to note, observe how high up the list is Fe and how far down is P. For every P atom there are nearly 2,000 C atoms and nearly 3,000 O atoms. For every 10 million grams of O's, there are 5 million grams of C's, 1 million of N's, 1 million of Fe's, half a million of S's, but only 7 thousand grams of P's. How much of molecular life can be based on H, C, N, O, P, S and Fe? Given that Avogadro's number is $\sim 6 \times 10^{23}$, there will be plenty of P's available for life, however, it may take special geophysical processes to produce mineral concentrates of it in the environment. These processes took place in special niches that would be the seats of life's origin. Hydrothermal vents of the primitive Earth may have been suitable, even ideal (note that today's hydrothermal vents are dense with life involving thermophilic bacteria that oxidize hydrogen sulfide, H_2S , using O_2 trapped by 6 foot tall tube worms that contain hemoglobin. One often reads and hears that this system uses chemosynthesis to get energy from H_2S without any involvement of the Sun. This is erroneous!! These are aerobic systems thriving on deep oceanic currents of cold water rich with dissolved O_2 . Rather than being primitive, these environments, all around the globe, are highly evolved modern oxidative systems. The oxygen is the product of Sun driven photosynthesis on the surface of the Earth [[Hydrothermal Vents](#)].

The second and third periods

Why is life based on the elements **H, C, N, O**, Na, Mg, **P, S**, Cl, K, Ca and **Fe**? Is this a cosmic accident here on Earth, or is this how it must be anywhere in the universe? This sort of question falls within a sequence of questions:

is mathematics universal?
 is physics universal?
 are inorganic and organic chemistry universal?
 is biochemistry universal?
 is the genetic code universal?

Most scientists would answer yes to at least the first two questions, but maybe not to all. Following the lead of George Wald, it will be argued below that the answer to all of these questions is probably yes.

Clearly, abundance plays some role in the answer because lighter elements are more abundant than the heavier ones. But while abundance is important *fitness* is just as important. Why certain elements are particularly fit for their role(s) will be explained.

By weight, $\frac{3}{4}$ of the Earth's crust is made of O (50%) and Si (25%), primarily as silicates. The oceans are mostly O (86%) and H (11%). Although Si is the second most abundant terrestrial element (7th in the Universe), it is highly unfit for living matter and, indeed, readily combines with O₂ to make silicates, for which it is much more fit. The free energy of formation of quartz from the elements O₂ and Si is -192.4 kcal/mol or -3.2 kcal/g. This is strongly negative compared to many other substances.

Name	Empirical formula	Molecular weight (gm/mol)	$-\Delta G_{298}^0$ (kcal/mol)	$\frac{-\Delta G_{298}^0}{g}$ (kcal/gm)
acetaldehyde	C ₂ H ₄ O	44	33.4	0.759
acetic acid	C ₂ H ₄ O ₂	60	94.7	1.578
acetate (aq)	C ₂ H ₃ O ₂ ⁻	59	89.0	1.508
acetyl CoA	C ₂₃ H ₃₉ O ₁₈ N ₇ P ₃ S	825	89.4	0.108
adenine (aq)	C ₅ H ₅ N ₅	135	-74.87	-0.554
adenosine (aq)	C ₁₀ H ₁₃ N ₅ O ₄	267	46.46	0.174
alanine	C ₃ H ₇ O ₂ N	89	88.7	0.997
ammonium ion (aq)	NH ₄ ⁺	18	19.0	1.056
arginine	C ₆ H ₁₅ O ₂ N ₄	175	126.7	0.724
asparagine	C ₄ H ₈ O ₃ N ₂	132	125.8	0.953
aspartate	C ₄ H ₆ O ₄ N ⁻	132	167.4	1.268
calcium (c)	Ca _n	40n	0.0	0.000
calcium (aq)	Ca ²⁺	40	132.2	3.305
calcium hydrogen phosphate	CaHPO ₄	138	401.5	2.909
carbon (c, graphite)	C _n	12n	0.0	0.000
hydrogen carbonate (aq)	CHO ₃ ⁺	61	140.3	2.300
carbon dioxide (g)	CO ₂	44	94.2	2.141
carbon dioxide (aq)	CO ₂	44	92.3	2.098

chlorine	Cl ₂	71	0.0	0.000
citrate	C ₆ H ₅ O ₇ ³⁻	189	278.7	1.475
creatine	C ₄ H ₉ O ₂ N ₃	131	63.1	0.482
cysteine	C ₃ H ₇ O ₂ NS	121	81.2	0.671
dihydroxyacetone phosphate	C ₃ H ₇ O ₆ P	170	308.9	1.817
erythrose 4-phosphate	C ₄ H ₉ O ₇ P	200	343.8	1.719
ethanol	C ₂ H ₆ O	46	43.4	0.943
formaldehyde	CH ₂ O	30	31.2	1.040
formic acid	CH ₂ O ₂	46	85.1	1.850
formate (aq)	CHO ₂ ⁻	45	83.8	1.862
fructose	C ₆ H ₁₂ O ₆	180	218.7	1.215
fructose 6-phosphate	C ₆ H ₁₃ O ₉ P	260	420.0	1.615
fructose bisphosphate	C ₆ H ₁₄ O ₁₂ P ₂	340	621.3	1.827
fumarate	C ₄ H ₃ O ₄ ⁻	115	144.3	1.255
galactose	C ₆ H ₁₂ O ₆	180	220.6	1.226
glucose	C ₆ H ₁₂ O ₆	180	219.1	1.217
glucose 6-phosphate	C ₆ H ₁₃ O ₉ P	260	420.5	1.617
glutamate	C ₅ H ₈ O ₄ N	146	166.5	1.140
glutamine	C ₅ H ₁₀ O ₃ N ₂	146	125.4	0.859
glycerol	C ₃ H ₈ O ₃	92	116.7	1.268
glycerol phosphate	C ₃ H ₉ O ₆ P	172	319.2	1.856
glycine	C ₂ H ₅ O ₂ N	75	90.0	1.200
glyceraldehyde 3-phosphate	C ₃ H ₇ O ₆ P	170	307.1	1.806
hydrogen (g)	H ₂	2	0.0	0.000
hydrogen cyanide	HCN	27	-28.7	-1.063
hydrogen sulfide	H ₂ S	34	6.5	0.191
hydronium ion (aq)	H ₃ O ⁺	19	56.7	2.984
hydroxyl	HO ⁻	17	37.6	2.212
iron (c)	Fe _n	55.8n	0.0	0.000
iron(II) (aq)	Fe ²⁺	55.8	20.3	0.364
iron(III) (aq)	Fe ³⁺	55.8	2.5	0.045
isocitrate	C ₆ H ₅ O ₇ ³⁻	189	277.1	1.466
isoleucine	C ₆ H ₁₂ O ₂ N	131	82.2	0.627
α-ketoglutarate	C ₅ H ₄ O ₅ ²⁻	144	190.7	1.324
lactate	C ₃ H ₅ O ₃ ⁻	89	123.4	1.387
lactose	C ₁₂ H ₂₂ O ₁₁	332	362.0	1.090
leucine	C ₆ H ₁₃ O ₂ N	131	85.1	0.650
magnesium (c)	Mg _n	24.3n	0.0	0.000
magnesium ion (aq)	Mg ²⁺	24.3	109.0	4.486
methane	CH ₄	16	12.1	0.756
methanol	CH ₄ O	32	41.9	1.309
nitrate ion (aq)	NO ₃ ⁻	62	26.4	0.426
nitrite ion (aq)	NO ₂ ⁻	46	8.2	0.178
nitrogen	N ₂	28	0.0	0.000
oxalate	C ₂ O ₄ ²⁻	88	161.2	1.832

oxaloacetate	$C_4H_2O_5^{2-}$	130	190.4	1.465
oxygen	O_2	32	0.0	0.000
phenylalanine	$C_9H_{11}O_2N$	165	49.5	0.300
dihydrogen phosphate ion (aq)	$H_2PO_4^-$	97	271.2	2.825
hydrogen phosphate ion (aq)	HPO_4^{2-}	96	261.4	2.723
phosphate ion (aq)	PO_4^{3-}	95	245.1	2.580
phosphoric acid	H_3PO_4	98	-274.1	-2.797
phosphorus (c, white)	P_n	31n	0.0	0.000
phosphoenolpyruvate	$C_3H_5O_6P$	136	303.3	2.230
potassium (c)	K_n	39.1n	0.0	0.000
potassium ion (aq)	K^+	39.1	67.5	1.726
pyruvate	$C_3H_3O_3^-$	87	113.4	1.303
quartz (c)	$(SiO_2)_n$	60n	192.4n	3.207
ribose (aq)	$C_5H_{10}O_5$	150	179.65	1.198
ribose 5-phosphate	$C_5H_{11}O_8P$	230	382.2	1.662
ribulose 5-phosphate	$C_5H_{11}O_8P$	230	381.7	1.660
sedoheptulose 7-phosphate	$C_7H_{15}O_{10}P$	290	457.1	1.576
serine	$C_3H_7O_3N$	105	122.1	1.163
silicon (c)	Si_n	28n	0.0	0.000
sodium (c)	Na_n	23n	0.0	0.000
sodium ion (aq)	Na^+	23	62.6	2.722
sodium chloride (c)	$NaCl$	58.5	91.8	1.569
succinate	$C_4H_4O_4^{2-}$	116	164.9	1.422
succinyl CoA	$C_{25}H_{40}O_{20}N_7P_3S$	882	164.0	0.186
sucrose	$C_{12}H_{22}O_{11}$	342	370.7	1.084
sulfate ion (aq)	SO_4^{2-}	96	177.3	1.847
sulfite ion (aq)	SO_3^{2-}	80	118.8	1.485
sulfur (c, rhombic)	S_n	32n	0.0	0.000
threonine	$C_4H_9O_3N$	119	122.9	1.033
tryptophan	$C_{11}H_{12}O_2N_2$	204	29.9	0.147
tyrosine	$C_9H_{11}O_3N$	181	92.5	0.511
urea	CH_4ON_2	60	48.7	0.812
valine	$C_5H_{11}O_2N$	117	86.0	0.735
xanthine	$C_5H_5O_2N_4$	153	33.3	0.218
xylulose	$C_5H_{10}O_5$	150	178.7	1.191
water	H_2O	18	56.7	3.150

Notable entries in this table are: ammonium ion (aq), calcium hydrogen phosphate, carbon dioxide (g), formaldehyde, glucose, glycine, phosphate ion (aq), quartz (c), ribose 5-phosphate, sulfate ion (aq), urea, and water. Calcium phosphate is the essence of the mineral apatite. Thus the available elements naturally produce a mixed population of molecules based on formation free energy relative to the building block elements (in the table the elements have 0 free energy of formation). Since many of these molecules are similar or identical with those in living matter, perhaps life utilizes what is available among naturally occurring small molecules.

About 99% of the constituents of living organisms are made of H, C, N, and O. Why these elements? The relative smallness of the atoms H, C, N and O enables them to make strong bonds with short bond lengths. H, O, N and C add respectively 1, 2, 3 and 4 electrons to achieve stable electronic configurations. Fluorine, F, also adds only 1 electron to achieve stability electronically, but it is outdone in this regard by H, which is smaller. Thus almost no F is found in living matter (some F occurs in teeth).

Adding electrons by sharing them with other atoms is the mechanism for forming chemical bonds, and, therefore, molecules. What has *smallness* got to do with it? The smallest atoms form the tightest, most stable bonds and they alone regularly form stable multiple bonds. In 1923, G. N. Lewis commented that “the ability to form multiple bonds is almost entirely, if not entirely, confined to elements of the first period of eight, especially to C, N and O.” Here, the terminology is different. The first period is for H and He only, and Li through Ne make up the second period. Lewis suggested that if it were not for these elements, the concept of the multiple bond might never have been invented. The occasions when one does encounter multiple bonds outside of this trio most frequently involve S and P. Knowledge of these other cases came some years after 1923.

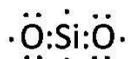
Comparing C and Si

In those places on Earth even remotely available to living organisms, Si is about 135 times as plentiful as C (cf. Universe abundance above). In the surface layers of the Earth, including the atmosphere, crust and hydrosphere, Si constitutes 16% of all atoms and C only 0.12%. Located directly under C in the Period Table, Si shares with C the property of tending to gain 4 e⁻s and so to form 4 covalent bonds by sharing e⁻s with other atoms. Why is life based on the rare C rather than on the prevalent Si? Strength and stability of bonding make up the difference.

Bond	Distance (Å)	Energy (kcal/mol)
C-C	1.54	80-83
Si-Si	2.34	42.2

To the extent that making organisms includes the capacity for tight stable bonds, and eventually long stable chains of atoms, C has a large intrinsic advantage over Si.

The capacity to form double bonds can be illustrated by comparing CO₂ with SiO₂. In CO₂, C is bonded to each O by double bonds, each involving the sharing of two pairs of e⁻s. By this means, each atom in CO₂ achieves a complete octet of outer shell e⁻s as in Ne. It is an atmospheric gas or readily dissolves in H₂O becoming *carbonic acid*. Si is joined to O by single bonds leaving two unpaired e⁻s on the Si and one on each O. Unable to pair by forming double bonds, these pair instead with the unpaired e⁻s on neighboring molecules of SiO₂. This process, repeated endlessly, ends in huge polymers of SiO₂. This is the basic structure of quartz, an extraordinarily dense, hard inert material.



Si has another fundamental disability relative to C. Like C, Si has a strong tendency to combine with itself to form chains. Potentially, Si compounds could exist in a variety and complexity rivaling C compounds. However, Si-Si bonds are unstable in the presence of H₂O, NH₃ and O₂ !! The reason for this is key to this discussion. In C, the outer shell contains one 2s and three 2p orbitals; these hybridize to sp³ orbitals, each of which is capable of being shared in 4 covalent bonds. This completes the octet and that is the end of it. In Si, however, the outermost electron shell is the third since Si is in the third period. When the vacant one 3s and three 3p orbitals have been filled, as a result of chemical combination, the atom has achieved a measure of stability, like that of Argon. However, completion of the octet of e⁻'s does *not* saturate the third shell. It possesses an additional five 3d orbitals, holding potentially five further pairs of e⁻'s. Thus, Argon isn't the end of it, Zinc is !! After Si has filled the octet by forming four covalent bonds, its outermost shell can still accept e⁻'s in the empty 3d orbitals. The molecules to which Si chains are most susceptible have small size and possess lone pairs of e⁻'s. The relatively large interatomic spacing in Si chains seems to allow such small molecules to come in close enough for their lone pair e⁻'s to occupy empty 3d orbitals in Si, and to disrupt the chain. Indeed, much the same attack is made on linkages between Si and other atoms than itself. For example, CH₄ is stable to H₂O and NaOH, whereas SiH₄ (*silane*) is attacked by these substances to form *sodium silicate* and H₂.



Therefore, there are three powerful reasons, one relative and two absolute, why Si is unsuitable as a basis for life: 1) it forms much weaker bonds than does C, both with itself and with other atoms; 2) its reluctance to form double bonds results in the formation of huge, inert covalently bonded polymers, thereby removing all but traces of Si from circulation; and 3) the instability of Si chains and compounds in the presence of O₂, NH₃ and H₂O.

The virtues of S and P

Nevertheless, it is precisely these disabilities of Si that create a special opportunity for P and S, especially for group transfer and energy transfer. What properties do S and P have that O

and N (the elements of the second period just under S and P in the third) do not have? There are three main answers: 1) S and P form more open and, in general, weaker bonds than do O and N; 2) S and P expand their covalent linkages beyond four on the basis of their 3d orbitals; and 3) S and P retain the ability to form double bonds. These three points are expanded below.

1)

Covalent bond radii (Å)

	C	N	O
single	0.772	0.74	0.74
double	0.667	0.62	0.62
	Si	P	S
single	1.17	1.10	1.04
double	1.07	1.00	0.94

Generally larger bond radii imply weaker bonds.

Bond energy (kcal/mol)

C-H	93.8
N-H	93.4
O-H	110.6
Si-H	70.4
P-H	76.4
S-H	81.1

Thus, in going from the second period N and O to the third period P and S one goes to more open and weaker bonds, hence to bonds more susceptible to attack and more ready to undergo cleavage and exchange reactions.

2)

Elements in the third period possess d orbitals in addition to the s and p orbitals possessed by their congeners in the second period. They have places to hold electrons beyond the normal outer shell octet of the second period. This distinguishes P and S from N and O. Phosphorous ordinarily doesn't go beyond five covalent bonds, as in PCl_5 (*phosphorous pentachloride*), and sulfur doesn't go beyond six, as in SF_6 (*sulfur hexafluoride*). Nothing comparable occurs for the congeners N and O. Just as with Si, these 3d orbitals in S and P invite attack by molecules possessing lone pairs of e^- 's.

3)

S and P possess the ability to form double bonds like C, N and O but unlike Si. How can this be? How can the 3d orbital properties be a boon to S and P and a liability to Si? The tendency to form double bonds may be associated with small size. Even though third period elements are bigger than second period elements, within a period, elements get smaller as the nuclear charge increases.

Covalent bond radii

	F	O	N	C	Cl	S	P	Si
single	0.64	0.74	0.74	0.772	0.99	1.04	1.10	1.17
double		0.62	0.62	0.667		0.94	1.00	1.07
At. No.	9	8	7	6	17	16	15	14

Thus, Si is the first element that is too big to form double bonds and at the same time it is too susceptible to attack by small molecules to form stable combinations. The only exception is the highly inert combination in quartz.

At this stage, one can imagine that life could be based on H, C, N, O, P and S. From considerations of energy metabolism, especially the electron transport chain, Fe is also a key ingredient. These seven elements form a basis set for life. Since proteins and polynucleotides are intrinsically charged species, electrical neutrality and related ionic necessities are met by a set of ions, Na^+ , Mg^{2+} , K^+ , Ca^{2+} and Cl^- . Thus, a mere dozen elements would appear to be sufficient for life. Even though certain other elements are found in essential functions in humans, such as iodine, copper, cobalt, zinc and selenium, it would not appear to be necessary to have these elements in the most primitive organisms.

Spontaneous formation of small molecules and monomers

Once the elements have formed and temperatures are low enough, a huge variety of small molecules form spontaneously from the elements. This spontaneity is measured by the Gibbs free energy of formation from the elements. A note of caution is in order, however. Associated with a spontaneous process is a decrease in Gibbs free energy. This in no way says anything about the rate. Thus, without adequate catalysis, a long time may be required before the low free energy products are actually formed. The Table earlier above lists the Gibbs free energy of formation for many compounds at 298 K. The table is for standard state conditions and since the Gibbs free energy change relative to the elements is negative, values are given for $-\Delta G_{298}^0$. Especially noteworthy are the very negative values for water, aqueous phosphate, silicates such as quartz, calcium phosphate, formaldehyde, amino acids, sugars and ribose 5-phosphate. It is useful to express these values in units of free energy per gram in order to compare values for compounds of very different structure and size. Once the small molecules and monomers have formed, the formation of oligomers and polymers is uphill in free energy.