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FROM THE PRIMEVAL SOUP TO WORLD GOVERNMENT: AN ESSAY ON COMPARATIVE EVOLUTION

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PREFACE

One of the most powerful tools of science is analogy. We used it in the search for guidelines for a possible general model of the evolution of man's energy procurement.

The choice of biosystems as the basis for the analogy, and the evolution in their ways of tapping primary energies, is purely heuristic.

We think a posteriori that the attempt has been fruitful, as the similarity between what man has done so far, and the problems biosystems had to face and the solutions they found, is very striking.

SUMMARY

The problems man is facing in his search for energy resources and ways of using energy should not be a priori different from those encountered by biosystems in the course of their evolution: we live in the same world and the rules of the game are similar.

How the analogy can be drawn is shown in this paper; so too is the excellent fit between the two evolutionary paths. A very tentative scenario is drawn for the future, by extending the parallelism a bit forward in time.

From the Primeval Soup to World Government - An Essay on Comparative Evolution*

As you heard from my booster, I'm really retired, so I can look at the world with a detached eye. And as you know I'm Italian. You may not be aware of the fact that the Italians, through a long history of intellectual trade with the Chinese, assimilated from them a number of basic reflexes.

Now the question I have leisurely been asking myself is whether all this circus of Hydrogen Economy, Hydrogen for the Future, Hydrogen the Ecomate, is a transitory fad or has some meaning in a larger context.

If I were American, I would set up a dynamic model of the world economy and try to guess what's the meaning of hydrogen through that model. Not being American, I do not like dynamic models--they too closely resemble cembalo-playing automatons. So what I did do is what any well-bred Chinese would do: look in the book of history to see whether a precedent exists, and from that precedent deduce the future--because history tends to repeat itself, and precedents contain physiological information about the ways things work in the real world. So in order to solve my problem I opened a very large book: the book of Nature, or more precisely the book of the Earth. I will try to convey to you the results of my observations, or, if you like, meditation and interpretation, as books--and in particular history books--have to be interpreted. This is somewhat equivocal because you may then put what you like into them, but I will try to rationalize my interpretation so that my personal feelings will not emerge.

Well, to begin at the beginning as Alice said, about four billion years ago the Earth started to take on what can be considered the soft form of its present state. It was a well-established planet in the solar system, the crust was solidifying, and the basic amount of gases, water in particular, had already come out of the degassing rocks. Our history then starts four billion years ago, or--as physicists say--four G-years ago.

The primeval atmosphere of the earth was essentially a reducing one. This may seem a point of detail, but it is extremely important. I can tell you in anticipation that most of our metabolism is based on a chemistry that is typical of a

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reducing ambient *just because* four billion years ago the atmosphere of the earth was a reducing one.

The reason why the atmosphere was in a reducing state is that the Earth as a whole is essentially in a reduced state. You can think of all the iron in the core of the earth as metallic iron, and it is natural for the gases coming out to be in a reduced state, or to become reduced--e.g. by the iron lying around at the surface. This atmosphere was made up of a very complicated mixture of gases: hydrogen, water, CO_2, nitrogen, ammonia, hydrogen sulphide; and the sun was injecting its usual amount of radiation into the system. So very probably there was also an atmospheric circulation, clouds, rain and lightning.

By various mechanisms, the energy introduced by the sun produced excitation and reactions between the molecules of the atmosphere, and quenching preserved the products even in non-equilibrium states. One can to some extent reconstruct what happened, for example by electric discharges in such a mixture of gases, and generate a complex set of molecules that we may call organic molecules because they are very similar to those produced by living organisms. Apart from electric discharges, other processes were active in this transformation, through ultraviolet light, the proton wind from the sun, and even hot magma. And this went on and on for a number of years, let us say half a G-year, without anything new really happening except a continuous increase in the number of these molecules concentrated in various configurations. One may have had the diluted solutions in large seas, and the concentrated ones and even precipitates in lakes, where evaporation and rain operated as a kind of soxlet. This is the "Primeval Soup".

The thermodynamic non-equilibrium of this broth, conserved by kinetic hindrances, constituted a negentropy dowry that gave purpose to astute manipulators. And the immense complexity and potential of organic chemistry gave them a chance. Although we have a fairly satisfactory log of information from geological evidence, from the immense capacity of living organisms to conserve information, and from continuity, what happened is in many ways obscure and certainly perplexing: some of the molecules banded together to rob other molecules of their free energy in order to support and reproduce their organization.

What these "catalysts" looked like is a fair guess, even if the rules of chemistry and of continuity greatly restrict the range of possible configurations. I like to see them as proto-viruses pilfering in concentrated pools of soup as they now exploit the protoplasm of cells.

In a reducing environment, the first self-organizing and reproducing catalytic systems could draw negentropy from a conceptually restricted number of operations, essentially molecular reorganizations, where hydrogen represented the mobile component. This hydrogen shuffling is called transhydrogenation and is at the base of all fermentation processes, and of the biochemistry of living systems.

This was probably the most momentous period in the whole evolution of life. The basic technology was created and established, and the basic invention of the founding fathers still constitutes the core of our metabolism. We, the man, are basically anaerobic fermenters with an "inboard" respiratory system.

The consequences of the technological breakthrough are easy to predict: faster and faster population growth, and exhaustion of the reserves that abiotic processes had accumulated in the primeval broth. In this Malthusian situation one can easily imagine the struggle for new biological niches--tricks for extracting negentropy from more and more sophisticated molecular scrambles and more and more and more diluted solutions.

The analogy with the last 200 years of the evolution of our society are striking, and you are probably burning to know what happens then. Final disaster to complete destruction of the biosystem? "Black death", reducing the level of life to the level of natural input of fermentable molecules? Development of "communes" characterized by less technologically aggressive behavior and stably fitted into econiches such as isolated lakes?

No. Actually the first half billion years of rapacious archeo-capitalistic exploitation of primary and non-renewable resources of soup had also generated something positive and of lasting value: an enormously sophisticated technology, flexible and capable of evolution--the technology of life. It is this that brought the technological fix to tap a new large source of negentropy.

The 300,000 TW of free energy the sun pours over the Earth were the obvious candidate source, although the ultraviolet component of sunlight, not yet filtered by the ozone layer, was an extreme radiation hazard for living organisms to deal with, genetic damage being the least thing that could happen and death the easiest. Sitting on top of three extra G-years we can safely say that there are other possibilities. One of them is to exploit fission or fusion, but in order to get to that the system still had to go through three fundamental breakthroughs: the eucaryotic organization, sex, and language.

Eucaryotic organization brought formally a centralization and rationalization of functions in the cell, but substantially the capacity to manipulate and control amounts of information larger by various orders of magnitude. Sex gave the possibility of transferring genetic information transversally, across the species, making the total genetic pool available for recombination. This enormously increased the speed of evolution, and hierarchically organized cell systems evolved up to man in a mere G-year.

Language plays a similar role, but evolution can now take a lysenkovian character and applies essentially to a kind of human ectoplasm: the machine.

Coming back to our desperate and courageous guys--the bacteria--they really had no option but the sun or bust. But how did they manage? One of various tricks invented during their "industrial revolution" was to separate the system capable of extracting free energy from the external molecules from the system using this energy. The separation was made by active chemi-osmotic membranes generating an energetic product which in its action very much resembles electricity: adenosintriphosphate.

This extraordinarily important and extraordinarily "archaic" energy carrier is certainly worth a digression. It was the basic energy carrier between the machinery operating the transhydrogenation and the living machinery synthesizing e.g. DNA and proteins. The rationale is that the increasing complexity of the mechanisms of life was isolated from the characteristics of the various primary energy sources, just as electricity "isolates" a computer from coal and oil chemistry.

The similarities of adenosintriphosphate (ATP) to electricity appear in various ways. First, it is a cycling molecule. It is made at a *phosphorylating membrane* (the fuel cell!) by attaching a phosphate ion to adenosindiphosphate (ADP). This requires about 8 Kcal/mole. It then reverts to ADP at the business end.

Now this chemical circulation is extremely fast, almost like that of electrons in a conductor. Just to give an idea, a man produces his weight of ATP every day, and consumes it: the amount of ATP present in our body is just a few grams. For bacteria the rate can be a thousand times higher.

ATP is a kind of DC electricity, and Edison would be happy with it, as it operates at a single voltage of about .15 V. There are no transformers and consequently it is not very transportable. It is in fact generated and consumed at the level of the cell travelling only a few microns. A reaction requiring a higher "voltage" is graded in a series of intermediate steps, each of them operable by ATP.

The breakthrough that led to the exploitation of light was the discovery that photosensitive pigments could be associated with the phosphorylating membrane, so that the pumping of electrons (or better protons) necessary to make ATP could be done through the absorption of quanta of light. In this way phosphorylation, i.e. production of ATP, could take place in the absence of fermentation. The fuel cell had become a photoelectric cell: photosynthetic bacteria had been invented.

Photosensitivity must have been around for a while, as a special case of chemical sensitivity. It was obviously an advantage to move in the right direction across the concentration gradients of the soup, and as it came down from the atmosphere, the soup was richer near its surface. But light, not filtered of its ultraviolet in the reducing atmosphere, was a killer, and had to be avoided. The new trick was really a relatively simple invention, but of sweeping importance. Incidentally, a single species of bacteria (perhaps a living fossil) still uses a vision receptor, retinal, for phosphorylation.

The laboratory-rigged photocell soon became an apparatus of intricate structure and high efficiency, but this is just development. The key issue is that sunlight was tapped. We too have tapped nuclear energy by making electricity first, for very similar reasons.

So "electricity" was produced by a photocell, and the free-energy umbilical link with the primeval soup was severed. However, if you keep growing other boundary conditions will pop up, and then you again start having problems, as the Club of Rome keeps reminding us.

The next problem was a materials procurement one: getting enough building material to make the biomass grow. It was normally quarried in the primeval soup, but through many mechanisms destroyed--broken down or not recycled. Oil may become short also for petro-chemicals after becoming short as fuel.

Now by far the largest amount of carbon available was in the form of carbon dioxide, and so the next step was to try to reduce carbon dioxide. The basic machinery already existed: bacteria had long used hydrogen, available from the atmosphere or from partial fermentation, to reduce CO_2 to methane. So the real problem was to find a new source of hydrogen.

A substrate from which hydrogen can be extracted relatively easily is hydrogen sulphide, and bacteria rapidly found a way to that. Most of the sulphur reserves we are mining now are just the tailings of this operation. What the bacteria were unable to do, however, with their low-voltage DC--that is, ATP produced by photophosphorylation--was to extract hydrogen from water, liberating oxygen as they liberate sulphur, an operation that is an order of magnitude more difficult.

Now bacteria trying to extract hydrogen from water by using light were in a situation extraordinarily similar to ours in trying to split water using nuclear heat. A single photon, even of blue light, had insufficient energy to pump an atom of hydrogen out of the water, just as the temperature of our reactors, even HTR, is insufficient to crack water thermally. But the restless exploration for new techniques finally led to the solution.

What the genius of the era hit upon was the simple and efficient idea of a *two-step* photochemical process to decompose water! The new organism--*the plant*--could now draw from the "infinite" resources of water, carbon dioxide and sunlight. So you see, by going from a single-step photoelectric process to a two-step photochemical process a quintessential breakthrough was reached in the living organism: independence, energetic independence and materials independence--and the umbilical link with the primeval soup was finally severed.

The problem of energy storage and transportation, so important later on for the development of complex organisms, was also solved at this point, as plants used the hydrogen to synthesize carbohydrates and fats. One is tempted to call them synthetic fuels.

Curiously enough, one of the ways explored by photosynthetic bacteria for extracting hydrogen from water, and occasionally used by them even today, required an oxygen acceptor to be taken from the soup and strictly resembles nuclear-assisted steam reforming of natural gas, or coal gasification, both one-step processes.

One of the side effects of this breakthrough was that immense amounts of oxygen were liberated. These slowly changed the essential nature of the primeval atmosphere, transforming it from a reducing to an oxidizing one. But the change was not only chemical. Most important, the presence of free oxygen in the atmosphere brought with it a change in the nature of the light reaching the surface of the Earth. As I said before, in a reducing atmosphere the ultraviolet tail of the solar light reached the surface of the Earth and would have destroyed the already sophisticated chemical mechanisms of the protobionts. They had to thrive in the warm womb of the ocean.

What the oxygen brought was a filtering of the short UV by the formation of an ozone layer in the stratosphere. Now living organisms could finally come out of the water and conquer the land. This can be viewed in another way; *life had grown to take control of the environment on a global scale,* and still holds it fast. To give one example of many, nitrogen is not at equilibrium in the atmosphere as it can combine with oxygen and water and go to a solution of nitric acid. This is thermodynamically possible and goes on all the time through various routes. Without a global counteraction the ocean would become a horrible pickle and life would be destroyed. The homeostatic feedback comes from a *geoengineering* operation of bacteria, living in the ooze at the ocean bottom or in the mud on land, which use the nitrogen oxides diffusing there to oxidize organic materials in the ooze. So oxygen is given back as CO_2, and nitrogen as such. Many such homeostatic feedbacks are operated by the biosphere, and this keeps our earth liveable.

Now, if humanity starts producing hydrogen from water using "new" sources of free energy--fission, fusion, or perhaps directly tapping the old sun--and moves away from fossil fuels, which in my analogy are the equivalent of the primeval soup, what kind of new control of the environment can occur as byproducts of this operation?

One of the reasons why I was led to the development of the hydrogen economy is the realization that the structure of an energy system is very strongly influenced by the physical and technological characteristics of the energy vector. I can give an example that comes from an existing energy system, the electric one. If you assume that electrical systems are continually reoptimized, you will find that a particular configuration that exists at a certain time results from the competition between two or three different requirements. One is that there is an economy of scale for a power station; this pushes toward building larger and larger stations. There is, however, a diseconomy in transporting electricity over large distances, and this asks the system for small, dispersed generating stations. And then the diseconomy of scale comes from the fact that the reliability or availability of the electrical net has to be much larger than the availability of a single power station, so that you must have a standby in case of machine failure. Standbys are cheaper if the machines are small, and so you have another force pulling towards small power plants.

Electricity is now transported at a mean distance of 100 km, and we'll call that the characteristic dimension of the unit cell. If you increase the transportability of your energy vector--say by using higher voltages, or better, by switching to hydrogen which has an economic transportability of about 1000 km--then the unit cell will grow to that size and the system will grow homothetically, with the optimal size for power stations 100 times larger than before.

A counter-proof of this reasoning comes from the evolution of the electrical system during this century, where the size of the cell doubled roughly every 22 years, and the density of the consumption inside the cell roughly every ten years. Combining the two growth factors, one finds a doubling of the power of the cell every 6.5 years. The statistics on the size of the largest generators installed during the last 80 years tell us their power consistently doubled every 6.5 years through five orders of magnitude!

Now with hydrogen as an energy vector, a unit cell of 1000 km takes the dimensions of a continent or a subcontinent: the USA may have three or four cells, Western Europe one or two, and the optimal size of the generating plants would be two orders of magnitude larger than for electricity.

That is for hydrogen transported by pipeline. But if we look farther into the future and assume that LH_2 can be economically generated and transported by tankers, as a kind of evolutionary trend of the present technology for liquid natural gas, then our economical distance may well become 10,000 km. Then the unit cell is the world, and the optimal configuration would be to generate all the energy on ten sites. Ten is the magic number that comes from the standby constraint in the optimization.

As humanity now uses about 7 TW of primary energy, each site would then have one TW and should obviously be located on the seashore or better on an island in the middle of the ocean. The investment per site would be in the order of hundreds of G-dollars, and this means that such an operation will become technically and economically the most important in the world. What could be the political implications?

In a nutshell, a State can be seen as a vertically integrated power system filling a geographical area. A multinational is a horizontal power system organizing a thin layer of human activities without precise geographical boundaries. The horizontal power generates "confusion" and loss of control by the vertical one and, with the layers thickening, will inevitably lock with it. The ostensible muck-raking against multinationals is a clear symptom of that. But what will be the outcome? Following my Chinese reflexes, I opened the history book again in search of precedents, and unexpectedly the search brought interesting results.

A fight between geographically bound political powers and a pervasive horizontal power went on in the Middle Ages. The multinational of the time was the Church, as you well know interfering and competing in many ways with the geographically fragmented political power of the time.

As the two power systems cannot be interchanged nor either one eliminated, a compromise finally had to be worked out. The political power handed its thin top layer to a supernational power structure, producing a kind of political multinational: the Holy Roman Empire. The manoeuvering space of the emperor was politically narrow, but territorially broad and at the proper hierarchical level of abstraction to deal with the Pope on an even basis.

My educated analogy says that the outcome will be a world government, or more flexibly defined, a world authority to make a dialogue possible.

Energy is the largest single business in the world. At \$12/bbl for oil the turnover is G\$500/year. It will be G\$2000 at the beginning of the next century. This means that energy multinationals will be the strongest forces in the struggle with the political power, and their field of activity a sensitive one. The system attraction of the ten-islands scheme will make this inevitable, and the issue exquisitely political.

Very large energy centers, and energy generation as a world operation, are direct consequences of the technological process of watersplitting, and they may modify the political atmosphere, just as oxygen did for the Earth atmosphere, leading finally to a world government.

The grand design is deploying itself, and we have the privilege and the responsibility of living at a great turning point in history.