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The Physics, Chemical Physics, and Biological Physics of the Origin of Life on Earth

Arthur S. Iberall
Retired Scholar, UCLA

This article illustrates the possible application of homeokinetics to the constructive process of the origin of life. The homeokinetic strategy is to seek out cycles at all time scales in a system where they can be discovered (spectroscopy) and to show how interacting cyclic processes can account for historical emergence of new entities, many of which also are cyclic processes. The full story of emergence necessarily begins with cosmology, which eventually results in an earth that can support geological processes, which form the matrix for life.

Biology and chemistry might be viewed as dominating the discussion about the origin of life. However, physics also has very useful insights to share. The intent of this article is—given the evolution and development of "purpose" in life systems wherein they can persist for a great number of generations—to determine the physical processes that can account for how the origin and evolution of many disparate species emerge as a regular procession of processes and events that began with the physics of the Big Bang.

Actually, four topics—physics, chemistry, geology, and biology—are part of a continuum that flows from physical processes and from the way humans process information. Physical science was born in the Enlightenment of the 17th century, and leads from Copernicus (ca 1500) to Newton (ca 1700; Randall, 1940; Wills, 1975). This new age of science led to the development of chemistry, geology, and biology. Chemical science began in the 18th century with Lavoisier. The coupling of ideas from these disparate fields led to an age of mechanism and machinery, and to an industrial revolution for engineering processes—civil (physical), mechanical,

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Requests for reprints should be sent to Arthur S. Iberall, 5070 Avenida del Sol, Laguna Woods, CA 92653. E-mail: aiberall@uci.edu

electrical, and chemical. Geological ideas coupled with biology when scientists were trying to understand fossils. This led to Darwin's theory of evolution and ideas on the development of life. By the 1950s it was obvious that all these processes were eminently physical and chemical (Cloud, 1970).

Homeokinetic physics, which defines the working of complex systems (Goodman, 1962; Iberall & McCulloch, 1969; Iberall & Soodak, 1987; Soodak & Iberall, 1978) shows that understanding real processes requires not only a physical description of time, space, energy, and matter, but also the historical pathways, the transformations, and the conservations that govern the interactions (Iberall, 1972). This enumeration typically begins with defining the end product (an origin to life) and then gathering into a coherent description all the competing, neutral, and cooperating processes.

PHYSICAL COSMOLOGY

The 20th century has offered a universal working cosmological model (Dermott, 1978; Peebles, 1993; Reddish, 1978; Shu, 1982; Soodak, 1987; Weinberg, 1977). The chronology of the current epoch starts at zero from the Big Bang.

In very brief Planck time after the Big Bang, elementary particles and quanta were created and gravitons decoupled. At about one-millionth second, protons and neutrons and their antiparticles formed by quark combination, annihilated with their antiparticles leaving behind in the universe a very small excess of protons and neutrons that represent our matter—protons, neutrons, neutrinos, antineutrinos, electrons and positrons, photons, and the decoupled gravitons. At about 1 sec, neutrinos and antineutrinos decoupled. At about 14 sec, electrons and positrons annihilated into photons, leaving behind the small number excess of electrons and the same number of protons. At 3 min, nucleosynthesis of protons and neutrons created helium nuclei (alpha particles). The universe at the beginning was then a plasma of protons, alpha particles, and electrons, with about 100 million photons per proton and the decoupled gravitons and neutrons. At 10,000 years, as a hot expansion continued to drive the gas-like plasma outward into the vacuum, the photon energy density, which was larger than the particle rest mass density at earlier times, now equaled it and was soon to fall below it.

At 300,000 years, the recombination era began. This may be considered as the beginning of a more normal state of the universe, because chemical elements come into existence during this era. Electrons and protons, which were driven apart from each other because of their high thermal kinetic energy, lost enough of that energy and cooled off, so that they began to "recombine" and include the alpha particles to form neutral hydrogen and helium. With this cooling, photons decoupled. At about 2 to 5 billion years ago (*Gya*) after the Big Bang, galaxies, clusters, and first-generation stars were formed. (The source material referenced all call those first generation Population II stars. The reader is asked to accept the apparent inversion of language.) The formation of these first-generation stars required the combination of electrical, mechanical, quantum, and nucleosynthetic processes. Some of the bigger stars proceeded through a shorter nucleosynthetic life before exploding as supernova, scattering the heavier elements beyond helium. By around 10 Gya, second-generation stars started to form and were "peppered" by the heavier elements from the explosions. Within this chronology, the second generation (of a Population I) star, our Sun, started up at about 5 Gya as one of billions of isolate stars appearing in the rotating arms of our spiral galaxy (therefore not a unique process). Galaxies now are loaded with billions of stars, typically with second-generation stars. There are also dust clouds containing solid particles of nuclear species. The stars most commonly form as binary pairs, and less commonly as single stars with a solar system of planets, planetesimals, and meteorites. From these processes, the terrestrial planets were the next to form. By 4.55 to 4.57 Gya, Earth and the other planets were present.

CHEMICAL COSMOLOGY

The chemical composition has been studied for each of these phases (Saxena, 1986; Shu, 1982). The second-generation stars are gas clouds of hydrogen with fractions of helium and peppered with even smaller amounts of other nuclear elements from lithium up through iron. Very minor concentrations of radioactive elements are present but are generally not indefinitely stable.

For background, the ancient Greeks introduced a prescientific protophilosophy laying out the presence of four ingredients: water, fire, air, and earth (Toulmin & Goodfield, 1962). The 20th-century universal cosmology substituted instead around 100 distinct nuclear atomic species. With these, the interaction of chemical and physical processes is the foundation from which I will attempt to derive life's origin. While this first article is responsible for the physics of life's originating processes, to be followed by a second article responsible for the chemistry, it cannot avoid presenting some reasonable tentative ideas about chemical processes.

EARTH PHYSICS

An understanding of geophysical processes in the interior of the earth is necessary to model life's geochemical–geophysical start-up at the surface. Indeed, all five major earth systems, the geophysical, the hydrological, the meteorological, the geochemical, and the biochemical, interact to create self-replicating living systems (Soodak & Iberall, 1978).

Mantle convection is one of the most important processes for driving life (Iberall, Wilkinson, & White, 1993). Following Gutenberg (1959), Robertson, Hays, and Knopoff (1972) provided a dynamic geophysics of the earth that incorporated plate tectonics as the major driving force.[1]

Although Beloussov (1975) did not believe in vertical plate tectonic movements, nevertheless his concept of lateral movement and the scaling data he provided from Russian sources led to an approximate 450 million year scaling process, which is empirically the time period for the mantle rolls of the Wilson Cycle. Contemporaneously, Vail and Mitchum (1979) were publishing on the global sea-level changes for the past 600 million years or so. The numerical magnitude between the interior process and the surface process is so similar that it seemed proper to ask if the mantle convection connected to the continental erosion process at the surface. Some parts of our relevant articles, Iberall and Soodak (1987) and Iberall et al. (1993, chap. 11), actually were written in the later 1970s. Turcotte and Burke (1978) approached the correlation by scaling sea-level changes with the thermal structure of Earth. Leliwa-Kopystynski and Teisseyre (1984) and Teisseyre (1986) fleshed out a rather complete internal planetary story for physicists. They provided an extended physical model of those interiors that even reached up to pressures for quantum processes (e.g., for stars).

These data sets were useful for modeling a layered earth, both inside and outside as far up to the region that the atmosphere becomes completely tenuous. First physical principles can account for the internal pressure, the temperature, the heat flow, the internal convective rolls, and the internal viscosity (Iberall et al., 1993). It thereby becomes not too difficult to connect the internal–external physical processes to their chemistry.

EARTH CHEMISTRY

Assuming with certainty that our Sun is a second-generation physical star in the galaxy, which is therefore not only hydrogen rich, but through prior neighboring nova and supernova explosions, it has run through a sequence of nucleosynthetic production processes and has been peppered in our galaxy to a cosmological abundance of other nuclei, particularly with some modest measure up through Fe (D. Anderson, 1989; Brush, 1990; Saxena, 1986). Assuming the “ansatz” (rule) that (effectively) every available chemical species will be used for life’s chemistry in pro-

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[1] Tectonics relates to the deformation of the crust of the Earth’s surface. Plate tectonics relates to the Earth’s crust, particularly large (e.g., near continental-sized) chunks that consist of plates floating on a near fluid molten rock upper mantle. The process of plate tectonics involves possible lateral movements of the separate plates, possible vertical plate movements, and movements of one adjacent plate under the other (“subduction”).

Plate tectonics relates to life’s origins because mantle convection in the Earth drives heat flow, which along with surface chemistry and surface energy flow, makes both life and its social structure on the Earth’s surface possible (Iberall et al., 1993). Therefore, it is important to understand the driving forces that create a fluid-like asthenospheric mantle and allow modeling its viscosity from very near first physical principles. The upper mantle turns over on the order of 500 to 600 million years (My; that is, the Wilson Cycle time scale).

portion to its abundance, the nominal chemical composition of each component is significant because of its bearing on the potential chemical composition of life.

The solar gas compositional abundances are provided as 14 species in a multielement system (Saxena & Eriksson, 1986). That system, at reasonable nebular temperatures and low pressures, leads in a sense to a phase diagram of solid and gaseous molecular constituents that might be found on the terrestrial planets. The averaged gas compositional abundances (as atomic elemental abundance per Si atom) are as follows: H (28,000), O (20), C (12), N (2.8), Mg (1.07), Si (1.0), Fe (0.88); S (0.51), Al (0.085); Ca (0.064), Na (0.059), Ni (0.048), K (0.0038), and Ti (0.0012).

Contrast this with the upper mantle composition (D. Anderson, 1989; Jeanloz & Knittel, 1986): O (atomic fractions 0.583), Mg (0.201), Si (0.158), Fe (0.022), Al (0.019), Ca (0.012), Na (0.0027), Cr (0.0011), Ni (0.0006), Mn (0.0003), and K (0.00004).

The mantle plus the crust has the following averaged composition (weight percent): SiO_2 (45.3), MgO (36.9), FeO (8.8), Al_2O_3 (4.1), CaO (3.3), Na_2O (0.29), NiO (0.46), S (0.39), and K_2O (0.028) (Saxena & Eriksson, 1986). The averaged composition of the core (weight percent) is Fe (85.4), S (6.4), O (8.0), and Ni (5.2) (Saxena & Eriksson, 1986). To grasp the material phase limitations from a near planetary surface atmosphere through all the near surface limitations, a very careful study has to be made of chapter 11 in Iberall et al. (1993).

EARTH ATMOSPHERE

The chemical composition of the early atmosphere has been approached from several directions. Cloud (1970) compiled a list of gases from those occluded in igneous rocks or those that are recognized as juvenile components of volcanoes and volcanic hot springs: H_2O, CO_2, CO, N_2, SO_2, HCl, and a few other trace gases. Sato (as cited in Robbins et al., 2000) listed gases he measured in inclusions in fresh lava that was not subjected to surface oxygen contamination: H_2O, CO_2, SO_2, H_2, CO, N_2.

Today, the atmosphere (Standard Atmosphere, 1974) is composed (mole fraction percent) N_2 (78.1), O_2 (20.9), Ar (0.9), Ne (0.002), He (0.0005), Kr (0.0001), H_2 (0.00005), and variable amounts of H_2O (0–4), CO_2 (0.035), CH_4 (0.0002), and O_3 (0.000004). It is not simple to provide answers for all the other solar planets, even if the study is limited to the terrestrial planets. The broadest comment that deserves expression is that many more people have to investigate each of these major heading issues, for they all are still in their infancy.

BIOLOGICAL CHEMISTRY

Certain complexities must be discussed to understand the links between physics, chemistry, and biology. It is clear that no physical chemist can handle a strict theory of a 14-element phase diagram. How many elements are needed to obtain a reasonable physical model for the terrestrial planets? If only H were available as H clouds in the galaxy, the condensed planetary density would be too low. SiO_2 is so abundant that Si and SiO atoms and molecules need to be added to the list. For life, H and HOH atoms and molecules, C and CO, and N and NO are needed. Add some near pure Fe compounds, and Cu at atomic number 29 is about the upper limit for required elements. What is so interesting about the H, C, and Si elements is that they can be thought of as hermaphroditic. That is, they can either be electron donors or acceptors. These have electrodynamic exchange valence electron bonding as well as electrostatic bonding. The elements CHON are sufficient for life (Morowitz, 1973, 1987), and the more exotic catalysts based on P and S probably were not that essential at the beginning of life's operation. With these six to eight nuclear elements and a few heavy radioactive ones, it is possible to provide an Earth model of the proper density, internal pressure distribution, internal temperature, internal viscosity, internal heat transport, and internal angular momentum distribution (Iberall et al., 1993).

Morowitz (1973, 1987) showed in a CHON reaction graph under reducing conditions that the rules of chemistry lead to the predominance of a small group of compounds. From his analysis, he noted that free radical reactions can dominate to form lipids through ethane and toward amino acids through the reactants for the Strecker synthesis: cyanide, ammonia, and an aldehyde. This has seemed to be a very impressive thought for the past 15 years or so. However, now as a chemist, M. Sato (personal communication, 2000) considered that the Strecker synthesis, although interesting, requires temperatures too high to consider it as an important reaction in the origin of life.

PALEONTOLOGICAL RECORD

The paleontological record is the place to start looking for evidence that only six to eight elements were involved with life's origin. The next question is where to begin the search, and using homeokinetic physics thought processes, it is important to first lay out the timing of various important processes.

Assuming that there is a physical foundation for the creation of sedimentary rock materials on Earth at 3.8 billion years ago (Gya), what is the evidence for water? Bedding and other sedimentary structures of microbially derived stromatolites in the Belt Series in Montana and the Swaziland System appear to be associated with lunar developed tides and have been dated (Glaessner, as cited in Cloud, 1970), which means that lunar capture goes back as early as 3 Gya. The association with tidal water processes indicates surface temperatures as low as a few hundreds of Kelvins. The limit for the end of meteoritic infall is 3.9 billion years ago (Iberall et al., 1993), which also suggests liquifaction of the surface until that time (Iberall et al., 1993, chap. 11).

It is important to recognize that almost as soon as the surface cooled, life began. Robbins, LaBerge, and Schmidt (1987) showed the presence of microbial shaped minerals that could be fossils of chemosynthetic organisms at 3.8 Gya, in Isua Iron Formation rocks in West Greenland where Mojzsis et al. (1996) found a phosphatic mineral. LaBerge (1967) rightly pointed out that microscopic remains may well be widespread in cherts of banded iron formations, but that they are generally so altered that most of their distinguishing features are lost and therefore their use for correlation and relative age determination are limited (Glaessner, 1970). However, Schopf and Walter (1983) showed the presence of unequivocal organic-walled body fossil of bacteria and cyanobacteria at 3.5 Gya in Warrawoona Formation rocks in Australia. Together, these data show that the first weathering of volcanic igneous rocks to sediment occurred in a hydrological cycle that existed at least by 3.8 Ga.

Getting to this point in our understanding required many studies that had to establish the changing chemistry of the ocean and the atmosphere, the formation and preservation of fossils, analysis of carbon isotopes, and a logical framework in which to understand the complexity of today's life. These steps included the work of Barghoorn (from the 1960s and earlier) who showed fossil remains encased in the Gunflint chert, which had to have invaded a dead object as a fluid and turn into a preserved solid that lasted for millions of years. His work pushed origins into the 1 to 3 Gya period. Cloud (1965) deduced that the atmosphere had to change from reducing to oxidizing with the precipitation of ferric iron in iron-formation. He ascribed this to oxygenic photosynthesis by cyanobacteria. Pflug (1978) discovered potential microfossils in the Isua Iron-Formation. LaBerge (1967) showed that a silica alga could have been involved in chert precipitation. Han and Runnegar (1992) showed multicellular algae in the Negaunee Iron-Formation, thereby establishing at least in a beginning way that iron was the important "metallo" element involved with organic compounds in eukaryote species. Schidlowski, Appel, Eichmann, and Junge (1979) showed that carbon isotopic values were organic as far back as 3.8 Ga. Wächtershäuser (as cited in Waldrop, 1990) calculated that pyrite dissolution could provide energy for life. Woese (1987) rooted life from a progenome that eventually produced the three extant kingdoms.

CHEMICAL AND PHYSICAL PROCESSES LEADING TO ORGANIC MOLECULES

The paleontological record, although quite rich, does not provide very useful information about start-up. Astronomy, however, has added some insights. The astronomer Sandage (1968) identified the clock of physical events in cosmology leading to Earth's processes and provided some physical conjectures on life as a self-organizing process. This led Iberall and Soodak (1987) to conjecture that the process of homogeneous catalysis of life probably took place within the early sedimentation beds 3.8 Gya. Shu (1982) helped to constrain the modeling and mechanism by which life could appear using insights from astronomy.

Experimentalists also have added useful insights. Miller and Urey (Miller, 1953) tested the chemical foundations for life by electrical discharge from lightning in a closed environment with water and gas components. This experiment never produced significant yield concentrations; amino acids were produced but the yield was too small (Iberall & Soodak, 1987). The Eigen-Schuster modeling (Schuster, 1987) suggested that polynucleotides are the most relevant examples of replication in biological systems. Orgel (1987) tried to produce long polymeric chains. This is the new feature that is emerging in biology, the enormous structural variety of biopolymers.

Other pieces of information come from biological thermodynamicists, for example, Morowitz, Kostelnik, Yang, and Cody (2000) who found that the citric acid cycle acts for intermediate metabolism in all primitive organisms. Beilstein's (1999) *Handbook of Organic Chemistry* data set was useful as a large empirical selection mechanism for isolating possible correct CxHyOz compounds rather than strict algorithmic rules. This search has winnowed down the selection to $x = 1–6$, and an otherwise infinite range for y and z to one not larger than 1–12. At most he has to consider perhaps 100 compounds. Biogeologist Robbins recognized that early life probably started around volcanoes and proposed in Robbins et al. (2000) that hot springs such as around Santorini, Greece discharged gas through a sediment bed. The high energy molecule formaldehyde (Sato, 1990) could be produced from H_2 and CO (Sato, Robbins, & Iberall, 2000). Sato and Robbins (personal communication) experimented with aldehydes and found that acidification of certain forms produced gunks. The best analogy for this reaction is the fractionating columns that Wallace Carothers (1975) used at Dupont to develop nylon.

In a fractionating column, particularly run by gravity, a column is stacked with "plates" or packed with resistive beds representing equivalent plate numbers. The function of the plates is to change the character of the axial flow compared to the radial flow. At some point down the column, side fractions are drawn off that represent rather pure components drawn off from the column with its changing flows and temperatures and pressure and concentrations. Carothers (1975), in the later 1930s, put in rather pure simple ingredients at the top of a reactor bed and by the time it trickled down it had produced a "gunk." Many chemists have made gunks, so that was not a complete surprise, but when Carothers went searching in that gunk for a different near-pure chemically complex compound, he found nylon.

The difference between putting pure ingredients at the top of a column and letting them trickle down is not so different from the natural system in which a volcano discharges pure gases from below and they move upward through sediment. The physical mechanism can be thought of as an antigravity machine, though not literally; it is a buoyancy machine in which gas ingredients rise. However, these bubbles are near pure molecular ingredients. They are CO, H_2, and SO_2, and possibly NH_3. A volcanic hot spring is an inverted fractionating column. The bubbling pours over like a fountain, providing a radial flow inward of defractionation, and forms a rising gunk, which represents inwelling of polymeric ingredients that can lead to or represent life.

Now the problem we have to demonstrate is whether any of those gunks produce enough time delays at long factory day time scales (Iberall, 1987; chap. 28 in Yates, 1987) to demonstrate periodically complex geochemical–biochemical subunits that fulfil reactions that can produce catalysts for thermophilic-like cellular forms.

BIOLOGICAL START-UP

The model for biological start-up therefore draws on many processes. Life's origins had to be volcanic in origin. It had to take place at a three-phase thermodynamic process among gas, liquid, and solid. It had to involve cycling among factory day processes that involved sedimentary materials. It had to involve the 500 My Wilson Cycle. Planetesimal infall on Mars is used to constrain life's emergence on Earth to a time frame after 3.9 Gya (evidenced by the number density of craters, indicating that the surface was fluid and that water was not yet condensed). It is also tied to the first appearance of sedimentary rocks on Earth at 3.75 Gya. Exploration of those rocks indicated putative evidence for biogenic forms (Robbins et al., 1987; Schidlowski et al., 1979). This suggests that life had started up in that 0.1 Gy period. The actual catalyst was probably a heterogeneous organometallic substance used by progenome. It had to relate in some way to the chemistry of the earliest rocks in West Greenland.[2]

Today, organisms catalyze life-producing reactions with photon pumping—organic dies (e.g., chlorophyll, anthocyanin) and ferrous-ferric iron pumps. Robbins and Harthill (in press) now suggest that cuprous–cupric pumping processes also may serve or augment iron. From these, thermophiles, methanogens, and halophiles came into existence. Yet what process was first? The abundance of iron-formation as the earliest rocks suggests iron pumping.

The coupling of catalysts such as these with volcanic bubbles allows the functioning of a slow process that could produce enough chemistry in 100 million years to produce a self-replicating molecule.

SYNTHESIS

In the introduction, I used the term *homeokinetic* physics to represent the conceptual framework of this article. Some of the emphasis in homeokinetics is on

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[2] The earliest solid mineral phases are igneous zircons that have been dated at 4.4 Gya (Kramers, 2001); these are detrital, meaning they were transported by water on a solid surface. The earliest sedimentary rocks, the supracrustal gneisses of West Greenland, are dated between 3.4 and 3.8 Gya (Kramers, 2001). Scherer, Munker, and Mezger (2001) used zircon data to suggest that Earth's first persistent crust formed between 60 and 260 My after the condensation of the oldest solid matter in the solar system (4.566 Ga), namely 4.51 to 4.31 Gya. Therefore, "Earth appears to have emerged from this Hadean era with liquid water and possible life already established on its surface" (Kramers, 2001).

its reductionism, but it is important to stress that the reduction is to a few principles. There can be many structures. However, mindful of P. W. Anderson (1972), it also is important to stress that homeokinetics is constructionist as well. We can say,

$$\text{Homeokinetics} = \text{Reductionism} + \text{Constructionism}.$$

In this article on physical (or chemical) origins for life, I offered the fractionating column as a constructive mechanistic (or chemical) process as a possible physical path to construct a living system, in a manner akin to the production of a "gunk" like nylon. Think of a factory for creating life in the bubbling springs of Santorini or Santorini-like environments.

Why can the description be either physics or chemistry? Because they both are made of atoms and molecules. Either synthesis is possible, as it suits you. I prefer to use physical mechanisms, but if and when it works, it can be reduced to a chemical chain. More examples are given in the Appendix.

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APPENDIX

Examples of Constructions—H = R + C Systems

1a. Two flat squares of wood assembled as a construction by the friction of a driven in nail.

1b. Two flat squares of wood assembled as a construction by the chemical action of a glue drop.

2a. A roll of glass wool insulation constructively produced from fine glass fibers as a “needled” production line process akin to carding fiber.

2b. A roll of glass wool wrapped around a hot water pipe as insulation, constructively held in place by duct tape.

2c. A roll of glass wool constructively held in place by a long string of knotted twine.

3. Radial and axial gravity flows of fluid material chemical complexes in a fractionating column "reactor" that constructively produces simpler chemical ingredients of greater purity.

4. Chemical and physical products made on production lines by companies like Dupont and General Motors.

5. The constructive transport of an impulse at a nerve cell synapse from neuron to neuron.

6. The constructive transport in an autonomic nervous system that governs involuntary actions in vertebrate animals.

7. Constructive transport systems in plants and trees.

8. Constructive animal—plant transport interchange systems (e.g. pollination).

9. Constructive activities organized for human clubs.

10. Constructive activities of corporations dealing with products or services.

11. Constructive activities organized in nation–states.

12. Constructive activities in stars, planetary systems, galaxies, cosmos, or the like in nature.

13. The constructive "spray-up" gun (as a hand held factory), which sprays a controllable mixture of three fluid streams: one of minute lengths of very thin fiber glass, one of a polyester fluid–plastic stream, and one of accelerator to control the plastic formation time. The novel constructionist step was that rather than trying to use very short life high quality and expensive machine tool material to cut the very strong glass fibers, because of their brittleness and fineness, they could be very easily cracked by intermittent small advances across an inexpensive single edged razor blade. Our client at Rand, Brunswick, wishing to use the material for high stress bowling alley surfaces, bought a boat company, and produced the spray-up gun that effectively makes all boats and large tanks in the world today. Boats are no longer made from wood (fastened by nails or glue), nor from metal (by pouring within a surface mold). They are sprayed in what has become the constructive basis for an industry worth billions of dollars.

ERRATUM

In the article by John Pickering, "On Revising Assumptions," Volume 13, Number 2, the last sentence of the second paragraph of the section "Neuropsychology Is Not Dangerous" (p. 148) should read, "Thus, so long as they are treated as complementary rather than definitive, neurological findings are a welcome adjunct to the ecological project."