Complex Systems: An Introduction

2. Anthropic Principle, Terrestrial Complexity, Complex Materials

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In Part 1 of this article (*Resonance*, August 2009) we introduced information theory and chaos theory, and discussed the computational nature of all phenomena, complex or simple. In this concluding part, we further emphasize the fact that the degree of complexity of a system depends in an important way on *our* perspective and prior understanding of the system. This anthropocentric aspect of complexity is exemplified in a dramatic way by the anthropic principle. We discuss the two main versions of this principle. This is followed by a description of the evolution of complexity in our ecosphere. Complexity in some 'nonadaptive' complex systems, namely complex materials, is also described briefly.

The Anthropic Principle

The anthropic principle was first enunciated by the mathematician Brandon Carter in 1974. Further elaboration and consolidation came in the form of a book by Barrow and Tipler [1]. A recent update has been given by Gefter [2]. The anthropic principle (two versions of which will be stated below) epitomizes the relentless evolution of complexity in Nature, exemplified by the emergence or evolution of humans, who are not only living but also *conscious* entities with a *free will*. It is instructive to first consider some terrestrial or planetary manifestations of the principle before taking up a more general discussion of the (controversial) 'strong' or cosmological version of the principle.

Keywords
Anthropic principle, evolution of complexity, the system Earth, nucleocultural energy regime, complex materials.

In particle physics and cosmology, we humans have had to introduce 'best fit' parameters (fundamental constants) to explain the universe as we see it. Slightly different values for some of the critical parameters would have led to entirely different histories of the cosmos. Why do those parameters have the values they have? The 'weak' or 'terrestrial' or 'planetary' version of the anthropic principle answers this question. This version says that: *the parameters and the laws of physics can be taken as fixed; it is simply that we humans have appeared in the universe to ask such questions at a time when the conditions were just right for our life*.

This weak version suffices to explain quite a few 'coincidences' related to the fact that the conditions for our evolution and existence on the planet Earth happen to be 'just right' for that purpose. Life as we know it exists only on planet Earth. Here is a list of favourable necessary conditions for its existence [3]:

- Availability of liquid water is one of the preconditions for our kind of life. Around a typical star like our Sun, there is an optimum zone (popularly called the 'Goldilocks zone'), neither so hot that water would evaporate, nor so cold that water would freeze, such that planets orbiting in that zone can sustain liquid water. Our Earth is one such planet.
- This optimum orbital zone should be circular or nearly circular. Once again, our Earth fulfils that requirement. A highly elliptical orbit would take the planet sometimes too close to the Sun, and sometimes too far, during its cycle. That would result in periods when water either evaporates or freezes. Life as we know it needs liquid water all the time.
- The location of the planet Jupiter in our Solar system is such that it acts like a 'massive gravitational vacuum cleaner', intercepting asteroids that would have been otherwise lethal to our survival.
- Planet Earth has a single relatively large Moon, which serves to stabilize its axis of rotation.
- Our Sun is not a binary star. Binary stars can have planets, but their orbits can get messed up in all sorts of ways, entailing unstable or varying conditions, inimical for life to survive and evolve.

Most of the planets of stars in our universe are not in the Goldilocks zones of their parent stars. This is understandable because, as the above list of favourable conditions shows, the probability for this to happen must be very low indeed. But howsoever low this probability is, it is not zero: The proof is that life does indeed exist on Earth.

The story of the incredible-looking set of favourable conditions for our existence does not stop here. What we have listed above are just some *necessary* conditions. They are by no means sufficient conditions also. With all the above conditions available on Earth, another rare set of phenomena occurred, namely the actual *origin* of life in the existing watery conditions. This origin was a set of chemical events, leading to *the emergence of a mechanism for heredity*. This mechanism came in the form of emergence of some kind of complex genetic molecules like RNA. Once life had originated, Darwinian evolution of complexity through natural selection did the rest and here we are, discussing such questions.

Like the origin of life, another rare event (or a set of events) was the emergence of the sophisticated eukaryotic cell (on which the life of we humans is based). We invoke the terrestrial anthropic principle again to say that, no matter how improbable such an event was statistically, it did indeed happen; otherwise we humans would not be there. The occurrence of *all* such one-off highly improbable events is explained well by the anthropic principle enunciated above.

It is not only that the planet we live on is conducive to our existence; even the universe we live in (with its operative set of laws of physics) is so. The cosmological or 'strong' version of the anthropic principle says that *our universe is what it is because we humans exist* [4]. Had it been inimical to our existence, we would not be here, discussing the anthropic principle.

As we know, the chemical elements needed for life were forged in stars, and then flung far into space through supernova explosions. This required a certain amount of time. Therefore the universe cannot be younger than the lifetime of stars. The universe cannot be too old either, because then all the stars would be 'dead'. Thus, according to the anthropic principle, life can exist only when the universe has just the age that we humans measure it to be, and has just the physical constants that we measure them to be [4].

It has been calculated that if the laws and fundamental constants of our universe had been even slightly different from what they are, life as we know it would not have been possible. Rees [5], for example, has listed six fundamental constants which together determine the universe as we see it. Their fine-tuned mutual values are such that even a slightly different set of these six numbers would have been inimical to human emergence and existence. Consideration of just one of these constants, namely the strength of *the strong interaction* (which determines the binding energies of nuclei), is enough to make the point. It is defined as that fraction of the mass of an atom of hydrogen which is released as energy when hydrogen atoms fuse to form an atom of helium. Its value is ~0.007, which is just right (give or take a small acceptable range) for any known chemistry to exist, and 'no chemistry' means 'no life'.

Our chemistry is based on reactions among the 90-odd elements. Hydrogen is the simplest among them, and the first to occur in the periodic table. All the other elements in our universe got synthesised by fusion of hydrogen atoms. This nuclear fusion depends on the strength of the strong or nuclear interaction, and also on the ability of a system to overcome the intense Coulomb repulsion between the fusing nuclei. The creation of intense temperatures is one way of overcoming the Coulomb repulsion. A small star like our Sun has a temperature high enough for the production of only helium from hydrogen. The other elements in the periodic table must have been made in the much hotter interiors of stars that are 8 times larger than our Sun. These big stars explode as supernovas, sending their contents as stellar dust clouds, which may eventually condense, creating new stars and planets, including our own Earth. That is how our Earth came to have the 90-odd elements so crucial to the chemistry of our life. The value 0.007 for the strong interaction determined the upper limit on the mass number of the elements we have here on Earth and elsewhere in our universe. A value of, say, 0.006, would mean that the universe would contain nothing but hydrogen, making impossible any chemistry whatsoever. And if it were too large, say 0.008, all the hydrogen would have disappeared by fusing into heavier elements. No hydrogen would mean no life as we know it; in particular there would be no water without hydrogen.

Similar considerations hold for the other finely-tuned fundamental constants of our universe. The 'reason' why they have the values that they do is that we humans exist; that is the essence of the cosmological anthropic principle. We can possibly discuss their values only in a universe that is capable of producing us. Our existence therefore 'explains' or rationalizes the measured values of these cosmological constants.

Such considerations hark back to the pioneering work of Hugh Everett, done fifty years ago (see [6] for a recent appraisal). Everett's 'many worlds' interpretation of quantum mechanics (in contrast to the so-called Copenhagen interpretation) is now taken seriously, particularly because of the current interest in quantum computing and quantum entanglement etc., [7].

What level of complexity was necessary for life to emerge on Earth? This is still a difficult question to answer. But the basic anthropic-principle approach appears to be applicable in a variety of contexts [3, 8].

Evolution of Complexity

Information content, by definition, is a measure of the degree of complexity of a system. Let us consider an open system, i.e., a system which can exchange energy and matter with its surroundings. The complexity of such a system can increase or evolve with the passage of time. How? The answer is: By an influx of information. Let us consider our own ecosphere as an example.

Energy drives all change. Our Earth receives most of its energy from the Sun [9], and the Sun produces it by thermonuclear reactions. The influx of solar energy into our ecosphere drives it away from equilibrium. Any system away from equilibrium will naturally tend to move back to equilibrium. Of course, any such process will take the system towards a state of higher entropy (as dictated by the second law of thermodynamics). Thus, if we take the equilibrium state as the reference state for specifying entropy, a pushing towards a state of disequilibrium can be thought of as an influx of 'negative entropy'. And since entropy is a measure of disorder, negative entropy connotes information. Thus what the Sun has been doing all the time is to increase the information content of our Earth.

This perpetual increase of information content is what has been driving evolution of various kinds. Evolution is not only biological; it can also be chemical, artificial, or cultural. Chemical evolution preceded biological evolution. Molecules of increasing complexity (or information content) evolved with the passage of time, and the emergence of metabolism and life was the inevitable next stage. Life just had to appear in the conditions prevailing on Earth. After the origin of life, biological evolution did the rest. It has been argued by the physicist Dyson that the emergence of self-replication properties was probably not a precondition for the emergence of life. Metabolism might have appeared first, and replication properties appeared in due course.

Thus the influx of energy (or information) is the reason for the ever-rising levels of complexity and evolution on Earth. Our entire ecosphere can be regarded as one single, highly complex, system ('the system Earth').

The System Earth

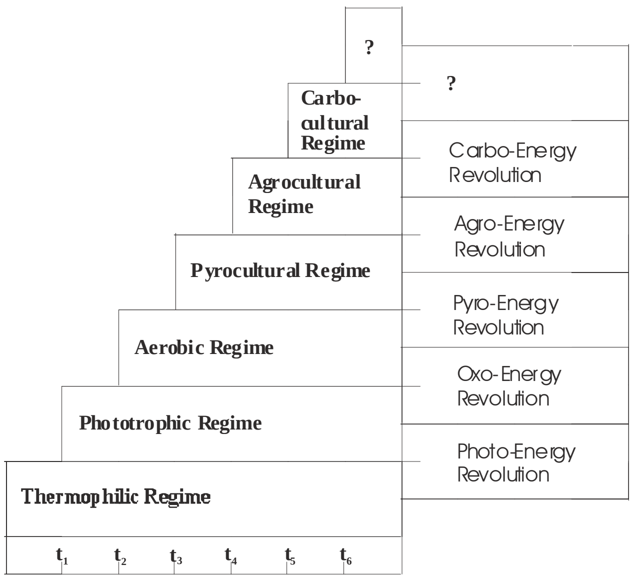
It is worthwhile to repeat and emphasize that evolution of all kinds requires an influx of energy. An evolutionary approach to the history of the Earth provides major insights into our current affairs [10]. Our energy-emitting Sun came into being ~4.6 billion years ago. The energy it emits in all directions comes from the thermonuclear fusion reactions taking place in it. Some of the energy emitted by the Sun is intercepted by our Earth, and then released in due course in a highly degraded (i.e., higher-entropy) form.

Most of the solar energy received by the atmosphere surrounding the Earth escapes from it directly back into outer space. If this were not so, the average temperature of the Earth would go on rising. What we have instead is a fairly constant average temperature. The tiny fraction of low-entropy (or high-quality) solar energy retained by the Earth drives processes such as photosynthesis. Some other sources of energy on our Earth are: geothermal energy; the cosmic microwave radiation; and the energy released by natural and artificial radioactivity. The energy flow in and around the Earth is influenced by the energy flows in the universe. A highly complex but delicate balance exists among solar energy, gravitational forces, nuclear reactions, and radiation [9].

As analysed by Niele [10], there have been five *energy revolutions* since the origin of life on Earth (see *Figure* 1): (1) The Photo-Energy Revolution (emergence of photosynthesis). This occurred ~3.8 billion years ago. (2) The Oxo-Energy Revolution (aerobic respiration). This occurred ~2.1 billion years ago. (3) The Pyro-Energy Revolution (domestication of fire by humankind). This occurred ~0.5 million years ago. (4) The Agro-Energy revolution. This occurred ~12,000 years ago. (5) The Carbo-Energy Revolution. This occurred ~400 years ago.

Each energy revolution heralded a new *energy regime*. This can happen if a new path for energy dissipation becomes available. (Both influx and dissipation of energy play a role in the evolution of complexity.) In the history of the Earth, the five energy revolutions separated six ecologically dominant energy regimes. These have been identified as [10]: (i) Thermophilic Regime. (The corresponding energy period is called the *thermion period*.) (ii) Phototrophic

Figure 1. Niele's [10] historical energy staircase for the system Earth, with near-constant influx of low-entropy energy (mainly solar energy). Plotted on the x-axis is time (not to scale). The y-axis depicts schematically the generally increasing degree of (terrestrial) complexity. Niele has identified the various energy revolutions (at times marked t_1, t_2, etc.), each such revolution heralding the onset of a specific energy regime. For example, the Photoenergy Revolution, which occurred at time t_1, marked the emergence of the Phototrophic Regime of energy. t_1 = ~3.8 billion years ago; t_2 = ~2.1 billion years ago; t_3 = ~0.5 million years ago; t_4 = ~12000 years ago; and t_5 = ~400 years ago. The time t_6 when the next energy revolution will occur is into the future, and is a question mark at present. We can only speculate about it. One possible scenario is that t_6 will mark the emergence of a Nucleocultural Energy Regime, heralded by a Nuclear-Energy Revolution.



Regime (*photian period*). (iii) Aerobic Regime (*oxian period*). (iv) Pyrocultural Regime (*pyrian period*). (v) Agrocultural Regime (*agrian period*). (vi) Carbocultural Regime (*carbian period*).

The reader is referred to the excellent book by Niele [10] for details about the various periods. We shall consider only the Carbocultural Energy Regime here, which is the regime we are currently living in. The Carbo-Energy Revolution occurred when humans discovered a fuel other than wood, namely fossil fuel (coal, petroleum, natural gas). This marked the onset of the Carbocultural Energy Regime. The fossil fuel had been created in the Aerobic Regime by the deposition of large volumes of dead biomass deep inside the Earth's crust.

Discovery of this new form of fuel resulted not just in its use in place of wood for burning, but led eventually to the development of *the combustion engine*. This development had truly far-reaching consequences. The engine converted heat to mechanical movement, resulting in locomotion, electricity production, etc. The availability of energy in a convenient form (electricity) led to a whole new set of societal energy-dissipating structures and emergent properties, apart from the phenomenal growth in population and economies. Niele [10] lists some of these developments: quantum mechanics, antibiotics, pop music, man on the moon, cities, the United Nations, unions, buildings, vehicles, medicines, computer networks, the world-wide web, mobile phones, etc. The explosive growth in the exploitation of fossil fuels has resulted in a steady build-up of carbon emissions in the atmosphere, which is now a cause for serious concern.

On the socio-technological side of the evolution of complexity, the Carbocultural Regime saw the grand alliance of science and crafts, giving rise to technology as we know it today. It is based largely on fossil fuels. Humankind has progressed from 'farms and villages' to 'cities and nations'. But humans in the Carbocultural Regime are turning against themselves by exceeding the carrying capacity of the habitat. This is a good example of how history repeats itself sometimes. Something similar happened in the Pyrocultural Regime and the Agrocultural Regime as well. In the Pyrocultural Regime, when the overshooting of the carrying capacity of the habitat occurred, the so-called 'symbolisational signal' [10] provided a new perception of reality, which enabled humans to increase the carrying capacity of the habitat by inventing agriculture. But in due course the Agrocultural Regime also reached a stage wherein the carrying capacity of the habitat was again exceeded. Once again, another signal, namely the so-called 'quantificational signal' provided the way out, in the form of exploitation of fossil fuels, heralding the emergence of the Carbocultural Regime.

We are in the Carbocultural Regime, and there is a clear signal about another overshooting of

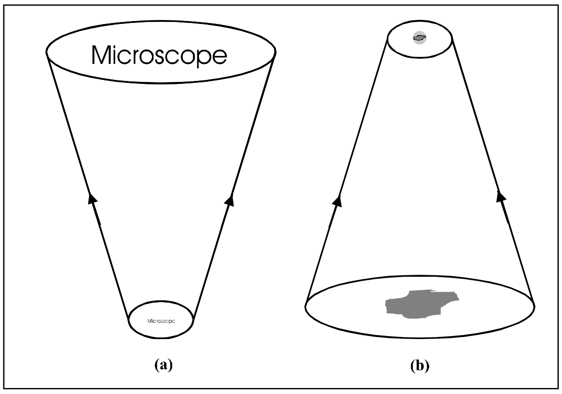


Figure 2. The microscope* versus *the macroscope. Microscopy, as in (a), is a case of zooming in, wherein we magnify details to see them more clearly. By contrast, macroscopy (b) is a case of zooming out. A macroscope is a conceptual instrument which combines data from various sources so that we can see* the big picture *in a way we can comprehend, without being encumbered by matters of too much detail.

the carrying capacity of the habitat. What we see now is the so-called 'macroscopical signal'. The term 'macroscope' is an apt one. Its meaning is just the opposite of 'microscope'. A microscope magnifies and shows details at small length scales (a case of zooming in). A macroscope is a 'symbolic instrument' which combines data from various sources and presents the big picture in a way we can comprehend (a case of zooming out) (*Figure* 2). de Rosnay [11] introduced this tool for investigating infinitely complex systems. A variety of macroscopical signals are impinging on our consciousness, and are making us acutely aware of problems like the global warming. Often the big picture is more helpful in finding a solution to a vexing complex problem.

Ecological footprint is another important term in this context. It is 'the area of productive land and water that people need to support their consumption and to dispose of waste'. The macroscopical signal is telling us that our ecological footprint is overshooting the carrying capacity of the habitat, and this can be dangerous.

Our response to the macroscopical signal is not unanimous. Two broad viewpoints have been identified, namely the 'Imperial view' and the 'Arcadian view' [10]. The former is an aggressive approach, aiming to control the complexities of Nature. The latter proposes humility in the face of forces of Nature, and aims at a life of harmony and peaceful coexistence with other creatures, advocating a reduction in the size of our current ecological footprint.

How will our energy needs be met? Fossil fuels cannot last forever. A new energy source must emerge, and according to the Imperial Man it must be nuclear energy. Nuclear fission is already being exploited for power production on a commercial scale. Second-generation nuclear reactors produce ~16% of the total electricity we consume. Third-generation reactors, with better safety and productivity features, went into operation a few years ago. Fourth-generation reactors, based on totally new approaches, are in the pipeline. But can nuclear-fission reactors *dominate* the energy scene for a long time to come, resulting in the emergence of a possible *Nucleocultural Energy Regime*, superseding the present Carbocultural Regime? Some people think that they can. Sustained research and development work can perhaps make available a large supply of fissile nuclear fuel, which may last for centuries, if not millennia. This hope is based on the utilisation of thorium, after uranium stocks have been exhausted. Breeder reactors add further to this sense of optimism.

Nuclear fusion, rather than fission, offers another kind of hope for the possible emergence of a Nucleocultural Regime, provided certain technological hurdles can be overcome. Both fission and fusion operate without emitting greenhouse gases. According to one estimate, it may be possible to operate a commercial fusion reactor by the end of this century. But this is only an estimate. One can never be sure about such complex matters. Whether or not a Nucleocultural Energy Regime will emerge is a difficult question to answer. The difficulty stems from the inherently unpredictable nature of complex systems. The ecosphere is certainly a most complex system. And so are human affairs. The complexity is not only of a scientific or technological nature, but also involves socio-economic issues ('game-playing') and political decisions.

The Nuclear Valley approach of the Imperial Man is to be contrasted with the Green Valley approach of the Arcadian Man. The Arcadian Man believes that it is futile to try to conquer Nature, and the most sensible thing to do is to live in harmony with it, and to ensure that all the other creatures with whom we share the Earth get their due share of the bounty. If this requires a reversal of the clock for shrinking our current ecological footprint, then so be it [12]. The Arcadian Man has no use for nuclear energy, nanotechnology, or genetic engineering. Even economic growth must be arrested, even reversed, if it has a deleterious effect on the ecosphere.

The Arcadian Man aims at using solar power, and emulating Mother Nature in cycling matter in (nearly) closed loops. Four hundred years ago, at the start of the Carbian Period, the man-made emissions of carbon dioxide, resulting from the use of fossil fuels, were so small that they could be readily processed and absorbed by green plants by photosynthesis. But today this emission has reached more than 24 G-tons per year, and natural processes can fix only a part of it into solid forms. Therefore, it is no longer tenable to go on following the practice of mostly 'linear' once-through conversion of natural resources into human waste. The macroscopical signal is loud and clear. We must resort to recycling matter in nearly-closed-loop metabolisms, so that the increasing burden on the ecosphere can be reversed. Innovative means must also be found for sequestering the carbon dioxide gas released into the atmosphere. Some possibilities are: reforestation; chemical fixation; injection into geological formations [13].

The moral of the story is that a better understanding of complexity in Nature is vital for our survival.

Except for the example of the whirlpool, most of our discussion in this article has been about what are called complex adaptive systems (CASs). Such systems have the distinctive feature that they undergo processes like learning and biological evolution (or biology-like evolution). They do not just operate in an environment created for them initially, but have the capability to even change their environment. For example, species, ant colonies, corporations, and industries evolve to improve their chances of survival in a changing environment. The marketplace adapts to factors like immigration, technological developments, prices and extent of availability of raw materials, and changes like those in tastes and lifestyles. On the other hand, galaxies and stars and other such complex objects and materials are examples of *nonadaptive* complex systems. They are inanimate systems which evolve with time, but within the unchanging constraints provided by the initial conditions and by the environment. We describe some complex materials here.

Complex Materials

Complex materials are composite materials (in a generalized sense). Composite materials are made up of two or more components or phases which are strongly bonded together in some desired connectivity pattern [14]. They are inhomogeneous solids. Artificial composites are designed to perform specific jobs. Natural composites may be either biological or nonbiological. The former have evolved as a consequence of some specific evolutionary processes. Composites can be classified as being either *structural* or *nonstructural* (the latter category is better known as *functional* composites).

A structural composite typically has a matrix, a reinforcement, and a filler. Reinforced cement concrete (RCC) is a structural composite, as are wood and particle-board.

Complex materials are a subset of functional composites, with the defining feature that not all their properties can be predicted from those of the component phases comprising the composite. Of particular interest in this context are the so-called *metamaterials,* which are artificially fabricated nanocomposites. Novel properties can be created in them by tailoring the shape, size, composition, symmetry, and connectivity, etc., of the component materials.

Multiferroics are the most important examples of nonbiological natural composites, as also of complex materials. Dominance of any of the electric, magnetic or elastic interactions in a ferroic material would normally give it a fairly definite ground-state configuration. But if there is close ('hairy edge') competition between two or all three interactions, there occur *competing ground states* [cf. 14]. A consequence of this is that, in the same crystal, different portions may order differently. Even the slightest of local perturbations (defects, inclusions, voids, composition variations, etc.) can tilt the balance in favour of ferroelastic, ferroelectric, or ferromagnetic ordering over mesoscopic length scales [15].

Anderson [16], in his famous 'more is different' paper, emphasized the emergence of complexity in a variety of condensed-matter systems. As happens even now, scientists sometimes tend to take the validity of both reductionism and constructionism for granted. Anderson pointed out that 'the reductionist hypothesis does not by any means imply a constructionist one: The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe. In fact, the more the elementary particle physicists tell us about the nature of the fundamental laws, the less relevance they seem to have to the very real problems of the rest of science, much less to those of society. The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear.'

Later, Anderson [17], in his path-breaking work on spin glasses, highlighted the role of *broken symmetry* for explaining the properties of a variety of complex materials. A fairly common theoretical framework has since been built up for describing spin glasses and their electrical and mechanical analogues, as also neural networks, protein folding, and several other networked complex systems [14, 18]. The spin-glass model was also invoked for understanding prebiotic evolution [19]. It was pointed out that only this model has the key features of both *stability* and *diversity*. The transition from inanimate molecules to life was interpreted as a spin-glass-like transition. It was argued that 'chance and necessity' alone cannot account for the transition to living systems even when aided by the phenomena of self-organization in dissipative open systems, and that chaos must be an additional precondition. It must have been necessary to have a survival probability that is a fixed but *chaotic* function of the molecular composition. The spin-glass model fulfils all these requirements.

Concluding Remarks

In this set of two introductory articles we have tried to give the student a feel for complexity in Nature by considering a few examples of complex systems, and by introducing some of the jargon used for dealing with complex systems. A common thread running through the behaviour of all complex systems is the *breakdown of the principle of linear superposition*: Because of the nonlinearities involved, a linear superposition of two solutions of an equation describing a complex system is not necessarily a solution. This fact lies at the heart of the failure of the reductionistic approach when it comes to understanding complex systems. Chaos is a particularly striking example of this situation.

Wolfram's work on complexity has led to the enunciation of his Principle of Computational Equivalence, which is a rather surprising result indeed. Actually it is more of a 'bold hypothesis' at present, although Wolfram is convinced that, in the years and decades to come, the validity and widespread applicability of the PCE will become more and more obvious.

At what point of time did the complexity of the universe, taken as a whole, start increasing? The moment of the big bang is a good point to start. From elementary particles to life and thinking organisms is a long journey indeed. 'As the wind of time blows into the sails of space, the unfolding of the universe nurtures the evolution of matter under the pressure of information. From divided to condensed and on to organized, living, and thinking matter, the path is toward an increase in complexity through self-organization' [20].

The availability of powerful computers has affected all branches of science, and the study of complex systems is no exception to that. However, it appears that there is something at the heart of complex systems which we do not understand yet. One is reminded of what Immanuel Kant said near the end of the 18^{th} century: 'It is absurd to hope that another Newton will arise in the future who will make comprehensible to us the production of a blade of grass according to natural laws.' We have certainly made progress since then but conceptual breakthroughs are still needed for a satisfactory level of understanding of complexity. At present there is also a question mark as to whether a unified description of complexity is at all possible. Are there more than one fundamentally different types of complexity?

Among scientists there are different perceptions about the meaning and importance of complexity in Nature. Here is one such viewpoint [21]: 'As science turns to complexity, one must realize that complexity demands attitudes quite different from those heretofore common in physics. Up to now, physicists looked for fundamental laws true for all times and all places. But each complex system is different: apparently there are no general laws for complexity. Instead, one must reach for "lessons" that might, with insight and understanding, be learned in one system and applied to another. Maybe physics studies will become more like human experience.'

Suggested Reading

[1] J D Barrow and F J Tipler, *The Anthropic Cosmological Principle*, Oxford University Press, New York, 1986.

[2] A Gefter, Exploring Stephen Hawking's flexiverse, *New Scientist*, p.28, 22 April 2006.

[3] R Dawkins, *The God Delusion*, Transworld Publishers, London, (paperback edition), 2007.

[4] M Chown, My other universe is a Porsche, *New Scientist*, p.38, 7 October 2006.

[5] M Rees, *Just Six Numbers*, Weidenfeld & Nicolson, London, 1999.

[6] P Byrne, The many worlds of Hugh Everett, *Scientific American*, p.98, December 2007.

[7] S Aaronson, The limits of quantum computers, *Scientific American*, p. 50, March 2008.

[8] K Mainzer, *Thinking in Complexity: The Computational Dynamics of Matter, Mind, and Mankind* (5th edition), Springer-Verlag, Berlin, 2007.
[9] F J Dyson, Energy in the universe, *Scientific American*, p.50, September 1971.
[10] F Niele, *Energy: Engine of Evolution*, Elsevier, Amsterdam, 2005.
[11] J de Rosnay, *The Macroscope: A New World Scientific Instrument*, Harper and Row Publishers, New York, 1979. First published in French in 1975.
[12] B van der Zwaan and A Petersen (eds.), *Sharing the Planet: Population – Consumption – Species*, Eburon Publishers, 2003.
[13] R L Nersesian, *Energy for the 21st Century: A Comprehensive Guide to Conventional and Alternative Sources*, M E Sharpe, London, 2007.
[14] V K Wadhawan, *Smart Structures: Blurring the Distinction Between the Living and the Nonliving*, Oxford University Press, Oxford, 2007.
[15] E Dagotto, Complexity in strongly correlated electronic systems, *Science*, p.257, 8 July 2005,
[16] P W Anderson, More is different, *Science*, Vol.177, p.393, 4 August 1972.
[17] P W Anderson. *Physics Today*. A series of six articles: January 1988; March 1988; June 1988; September 1988; July 1989; September 1989.
[18] V K Wadhawan, *Introduction to Ferroic Materials*, Gordon and Breach, Amsterdam, 2000.
[19] P W Anderson, Suggested model of prebiotic evolution: The use of chaos, *PNAS, USA*, Vol.80, p.3386, June 1983.
[20] J-M Lehn, Toward complex matter: Supramolecular chemistry and self-organization, *PNAS, USA*, Vol.99, No.8, p.4763, 16 April 2002.
[21] N Goldenfeld and L P Kadanoff, Simple lessons from complexity, *Science*, Vol.284, p.87, 2 April 1999.

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