How Big History Works: Energy Flows and the Rise and Demise of Complexity[1]

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ABSTRACT

In this article, I advance an explanatory scheme for all of history from the beginning of the Universe until life on Earth today (big history). My scheme is based on the ways in which energy levels as well as matter and energy flows have made possible both the rise and demise of complexity in all its forms.

INTRODUCTION

Surely, any claim to explain all of history must sound preposterous. So let me be clear about my aims and claims. To begin with, I do not claim to have found exhaustive explanations for every little thing that has ever happened in history. Far from it. Explaining any part of the past always means striking a balance between chance and necessity. My explanatory scheme is about necessity. It consists of general trends that make possible and constrain certain forms of complexity. Yet within these bounds, there is ample room for chance. Although in this essay I do not systematically focus on chance, the reader should keep this in mind[2].

The central concepts of my scheme are matter, energy and entropy (disorder). This will be elaborated below. Seen from the modern scientific point of view, everything that has existed has been composed of matter and energy of some sort. A major advan-

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tage of using such general terms is that they are applicable to all aspects of big history. A second major advantage is that no new physics are needed in order to understand the course of big history.

I see my explanatory scheme as a further elaboration of concepts explained in my book *The Structure of Big History* (1996). There, I proposed to employ the term *regimes* for all more or less structured processes that make up big history. Now, it seems to me that regimes are not only very useful for describing big history but also for explaining it.

In addition to the general insights into the workings of matter, energy and entropy that I gained during my career in chemistry, my understanding of energy flows has been strongly influenced chronologically by the writings of Marvin Harris (1975, 1980), Jeremy Rifkin (1981), I. G. Simmons (1993, 1994), David Christian (over the period 1991–2004), Ilya Prigogine and Isabelle Stengers (1984), Stuart Kauffman (1993, 1995), Eric Chaisson (over the period 1981–2005), Erich Jantsch (1980), Vaclav Smil (1994) and Leslie White (over the period 1943, 1975)[3]. My argument leans heavily on Eric Chaisson's scholarship, most notably his book *Cosmic Evolution: The Rise of Complexity in Nature* (2001), and also on David Christian's work: his article 'The Case for "Big History"' of 1991 and his book *Maps of Time: An Introduction to 'Big History*' published in 2004. Also the historian John R. McNeill recently wrote an overview pointing in the same direction (2003: 319–323). The synthesis presented here must, therefore, to a considerable extent be considered a communal product.

As a result of limited space, in this article I have stripped the argument down to its barest essentials. Many nuances, examples and elaborations needed to be scrapped. Those readers who are not satisfied by this approach will have to wait until my book on the same subject will appear in print, hopefully in a few years' time.

COMPLEXITY AND COSMIC HISTORY

The history of the Universe is the history of emerging complexity. In the beginning there was no complexity at all. The further the

Universe evolved the more complex some portions could become. Right now, after about thirteen billion years of cosmic evolution, the human species is arguably the most complex organism in the entire known Universe.

Seen from the most general point of view, complexity is a result of interactions between matter and energy, resulting in more or less complex arrangements of matter (I will call them *matter regimes*). Cosmic history, therefore, primarily deals with the question of how these matter regimes have formed, flourished and foundered over time. Unfortunately, no generally accepted definition exists of how to determine the level of complexity of matter regimes. Yet there can be no doubt that it makes sense to call certain regimes more complex than others. Who, for instance, would be willing to argue that a bacterium is more complex than a human being, or a proton is more complex than a uranium nucleus? Apparently, the numbers of the building blocks of a certain matter regime, their variety, and their interactions jointly determine the level of complexity. I would therefore argue that a matter regime is more complex when more, and more varied, interactions take place among increasing numbers of the ever more varied building blocks of which the regime consists. In other words, a regime is more complex when the whole is more different than the sum of its parts (Chaisson 2001: 12–13).

From the perspective of big history, the highest complexity appears to exist on the surfaces of celestial bodies situated on the outer edges of galaxies. In other words, higher complexity is typically a marginal phenomenon, both in the sense that it can be found on the margins of larger regimes and in the sense that it is exceedingly rare. Most of the Universe consists of lesser forms of complexity. To be sure, as Eric Chaisson observed, this is not true for life itself. The highest biological complexity, most notably DNA and brains, are to be found in, or near, the center of their regimes and not on their edges. Apparently, this type of higher complexity needs to be protected against matter and energy flows from outside that are too big, in which case it would be destroyed, or too small, in which case it would freeze. In other words, life has created a space suit for its own highest complexity. In fact, terrestrial life may have well succeeded in turning the entire biosphere into a space suit. This is, in my view, the essence of James Lovelock's Gaia hypothesis, which states that terrestrial life has evolved feedback mechanisms that condition the biosphere in ways that are advantageous for life's continued existence on our planet.

THREE FUNDAMENTAL TYPES OF COMPLEXITY

Three major types of complexity can be discerned: physical inanimate nature, life and culture. Let us start with physical nature. First of all, it is of great importance to see that most of nature is in fact lifeless. The following example may help to grasp the significance of its sheer size. For the sake of simplicity, let us assume that the Earth weighs as much as an average American car (about 1000 kg). The weight of all planetary life combined would then amount to no more than seventeen micrograms. This equals the weight of a very tiny sliver of paint falling off that car. Seen from this perspective, the total weight of our Solar System would be equivalent to the weight of an average supertanker. Since the mass of the Universe as a whole is not well known, I refrain from extending this comparison any further. But even if life were as abundant in the Universe as it is within our Solar System, its relative total weight would not amount to more than a tiny sliver of paint falling off a supertanker.

All this cosmic inanimate matter shows varying degrees of complexity, ranging from single atoms to entire galaxies, and it organizes itself entirely thanks to the fundamental laws of nature. Although the resulting structures can be exquisite, inanimate complexity does not make use of any information for its own formation or sustenance. In other words, there are no information centres dictating what the physical lifeless world looks like. It does not make any sense to wonder where the information is stored that helps to shape the Earth or our Solar System.

The next level of complexity is life. In terms of mass, as we just saw, life is a rather marginal phenomenon. Yet the complexity of life is far higher than anything attained by lifeless matter. In contrast to the inanimate Universe, life seeks to create and maintain the conditions suitable for its own existence by actively sucking in matter and energy flows with the aid of special mechanisms. As soon as living things stop doing this, they die and their matter and energy return to lower levels of complexity (unless they are consumed by other life forms). Life organizes itself with the aid of (mostly hereditary) information stored in molecules (mostly DNA). While investigating living species, it does make a great deal of sense to wonder where the information centres are, what the information looks like, and how the control mechanisms work that help to translate this information into biological shapes.

The third level of complexity was reached when some complex living beings began to organize themselves with the aid of cultural information stored as software in nerve and brain cells. The species which has developed this capacity the furthest is, of course, humankind. In terms of total body weight, our species currently makes up about 0.005 per cent of all planetary biomass. If all life combined were just a tiny sliver of paint falling off a car, all human beings today would jointly amount to no more than a tiny colony of bacteria sitting on that flake. Yet through our combined efforts we have learned to control a considerable portion of the terrestrial biomass, perhaps as much as 25 to 40 per cent. In other words, over the course of time this tiny colony of microorganisms residing on a sliver of paint has succeeded in gaining control over a considerable portion of that flake. We were able to do so with the aid of culture. In its barest essence, culture consists of accumulated learned experiences stored as software in our brains and nerve cells or in human records. In order to understand how human societies operate, it is therefore not sufficient to look only at their DNA and their molecular mechanisms. We need to study the information humans use to shape both their own lives and the rest of nature.

ENERGY FLOWS AND COMPLEXITY

During the history of the Universe, all the major forms of physical, biological and cultural complexity apparently emerged all by themselves. In the scientific approach, the possible influence of supernatural forces bringing about complexity is not considered to be an acceptable explanation, since we have never observed such forces at work. The major question becomes therefore: how does the cosmos organize itself? This question becomes even more difficult by realizing that, in our daily lives, we often observe the opposite: the breakdown of complexity into chaos. Children's rooms, for instance, never clean themselves up all by themselves and, without a trash collecting system, cities would soon choke in their own refuse. This breakdown of complexity into chaos is known as the Second Law of Thermodynamics. This law states that over the course of time, the level of disorder (entropy) must increase. In other words, the history of the Universe must also be the history of increasing disorder. Any local rise in complexity must, therefore, inevitably have been accompanied by a larger rise of disorder elsewhere.

According to the modern view recently expressed by, among others, Ilya Prigonine and Isabelle Stengers and Eric Chaisson, complexity emerges when energy flows through matter. Only in this way it is possible for more complex structures to arise. But what does the concept of energy flows mean? This is not as straightforward as it may seem. Eric Chaisson defines *free energy rate density* – indicated with the symbol Φm – as the amount of energy per second that flows through a certain mass (free energy is energy able to perform useful tasks; this means an energy differential exists which can be tapped). Chaisson next shows that there is a clear correlation between levels of complexity and his calculated *free energy rate densities*. This is the central argument of his book *Cosmic Evolution: The Rise of Complexity in Nature* (2001)[4]. Although, compared to most other aspects of big history, humans may seem vanishingly small, according to Chaisson we have generated by far the biggest *free energy rate densities* in the known Universe.

Surprisingly little attention has been devoted to the demise of complexity[5]. Seen from the highest level of generality, complexity is destroyed when the energy flows and/or energy levels (temperatures and pressures) become either too high or too low. For instance, without a sufficient energy flow, no biological regime will survive. Yet if such an organism experiences energy flows that are too big, it will succumb to them, too. This is also true for lifeless regimes, such as rocks, planets or stars. All matter regimes are, therefore, characterized by certain bandwidths of energy levels and flows within which they can exist.

THE BIG BANG AND THE RADIATION ERA

According to our modern creation story, at the beginning of time and space there was a lot of undifferentiated energy/matter packed extremely close together. At the instant of creation, the Universe was infinitely dense and unimaginably hot. At that very moment, the Universe was entirely undifferentiated. In other words, the instant of the big bang was the most simple and basic regime imaginable.

During the first period of cosmic expansion, temperature differences were very small, if they existed at all. Yet as a result of the cosmic expansion, temperatures began to drop. Radiation dominated the early Universe, while stable matter did not yet exist. Although some conversion of energy into matter would have occurred, the radiation was so strong and temperatures so high that any matter that had formed was immediately destroyed again. In other words, the circumstances were not right for any formation of material complexity. Eric Chaisson therefore calls this early phase of cosmic history the *Radiation Era*. At that time, as Eric Chaisson emphasizes, entropy was at a maximum. It is, however, not completely clear whether radiation was completely uniformly distributed during this period. Current measurements of the cosmic background radiation show minor fluctuations. I wonder whether this provides an indication of some complexity of the energy regime of the early Universe.

The Radiation Era witnessed the emergence of the three basic forces that organize matter: the nuclear force, electromagnetism and gravity. The first level of material complexity would later be reached as a result of the nuclear force – which acts by far the strongest on very short distances. This complexity consisted of the smallest, subatomic and atomic particles. Electromagnetism, the intermediate force, would take care of the second stage, in which atoms, molecules and complexes of molecules were formed. The effects of gravity, the weakest of the three forces but with the longest reach, would kick in the last and would bring about all the larger structures in the observable Universe.

THE MATTER ERA

After about 10,000 years of cosmic expansion, the Radiation Era came to an end. By that time, the temperature of the early Universe radiation had dropped to around 10^7 Kelvin. At this temperature and below, the nuclear force was no longer overwhelmed by the energy levels prevailing. As a result, more stable ordinary matter, mostly subatomic and atomic particles, had begun to form. This led to the separation of energy and matter. Yet according to the standard cosmological view, most of these subatomic and atomic particles that were originally formed soon annihilated one another and were reconverted into radiation. Only a tiny fraction of ordinary matter survived. This left-over stuff constituted the building blocks for all the known material complexity that followed.

Since the Universe kept expanding, the temperature of the radiation kept dropping. As a result, the importance of radiation decreased. Cosmic expansion had, however, no similar effect on matter. Although, seen on the scale of the Universe, matter became more diluted, the particles themselves did not change in nature. As a consequence, relatively speaking, matter became increasingly important. According to Eric Chaisson, the *Matter Era* had begun. This transition marked the first formation of stable material complexity. During the early phase of the Matter Era, only a few types of small building blocks of matter existed, mostly protons, neutrons and electrons. No heavy chemical elements were formed yet. The expansion would have gone so very quickly that the conditions of high temperatures and pressures needed to cook heavier elements did not prevail for long enough. As a result, the possibilities for higher complexity in the early Universe were limited.

Here we see a critical factor for the formation of complexity in operation, namely time. It takes time, often a great deal of time, for complexity to emerge. In certain situations, the energy flows and levels may be right for the emergence of higher levels of complexity. Yet if such conditions prevail for only a short period of time, no substantial amounts of such complexity can form. The destruction of higher levels of complexity, by contrast, can take place very quickly indeed.

After about 300,000 years of expansion, the Universe had cooled down to about 10^4 Kelvin, while the pressures had been dropping also. These lower energy levels allowed negatively and positively charged particles to combine for the first time and form matter regimes of higher complexity, first atoms and later molecules. This process had a marked effect on radiation, since it is far less affected by neutral particles than by charged ones. Radiation could now suddenly travel throughout the Universe virtually unimpeded. As a result, the Universe became transparent. The cosmic background radiation we observe today dates back to this monumental change.

This ‘neutralization’ of the Universe also marked an important transition for the factors which determine the levels of material that can be attained. Before that time, only the energy levels limited the levels of material complexity. Yet after about 300,000 years of cosmic expansion, the formation of complexity would come as a result of the interplay between energy levels and energy flows. Since that time, all subatomic complexity has been determined by the nuclear force (in some conjunction with the ‘weak force’, now thought to be part of electromagnetism). The intermediate scales of complexity, from atoms and molecules up to stars and planets have come as a result of the electromagnetic force and of gravity, while all the large-scale complexity, ranging from our solar system to galaxy clusters, has been shaped by gravity.

According to Eric Chaisson, cosmic expansion has been vital for the formation of complexity (2001: 126). Because in the early Universe entropy was at a maximum, for complexity to form, some sort of entropy trash can was needed, since the formation of local or regional order requires the formation of more disorder somewhere else. The continuing expansion of the Universe provided increasing room for entropy, and thus functioned as a huge entropy trash can, which can take up low level energy, most notably heat. And as long as the Universe keeps expanding, the cosmic entropy trash can will get bigger. As a result, it can store increasing amounts of low level energy. This – and this alone – allows energy levels to keep flowing and higher complexity to exist.

While the cosmic trash can was getting bigger, another major trend started: energy differences began to level out. Both these processes have made possible the rise of complexity. Since the energy supplies of the Universe as a whole are not being replenished, and assuming that the Universe will keep expanding for the foreseeable future, the long-term effect of all these effects will be the overall increase of entropy everywhere. In other words, in the very long run the Universe will become a rather dull place.

GALAXY FORMATION

The unrelenting expansion of the Universe led to a further decrease of the temperature levels. As a result, gravity began to shape the ways in which matter clung together. Since that time, gravitational energy has driven the formation of larger structures, ranging from asteroid-sized clumps of matter to clusters of galaxies. Only during the first billion years or so were the conditions right for galaxy formation. Even while they were being formed, most galaxies began to fly away from one another. This defines, in fact, the expansion of the Universe. In a number of cases, however, gravity kept galaxies close together, while some galaxies actually merged with others. Yet with the passage of time, these occurrences diminished in importance.

While the Universe kept expanding, the galaxies appear to have retained their original sizes more or less. As a result, the Universe became more differentiated. Over the course of time, within galaxies higher levels of complexity would arise. The expanding intergalactic space, by contrast, was mostly empty and would therefore never become very complex. Yet intergalactic space did provide a cosmic trash can for low level energy produced in galaxies. This made possible the rise of higher complexity within galaxies.

The cores of newly forming stars within galaxies began to produce circumstances that were similar to the early stages of the Matter Era. Temperatures rose to 10^7 Kelvin and above, while pressures would go up to 10^{11} atmospheres and higher. The major difference with the early Matter Era was that stars last far longer than the period in which the first elements were cooked. This means that there was far more time available to produce higher elements. As a result, stars would become the major furnaces for producing higher levels of nuclear complexity.

The mechanism which drove this process was nuclear fusion. After enough hydrogen nuclei had gathered under the influence of gravity, temperatures and pressures would rise to the extent that nuclear chain reactions could ignite, forging one helium nucleus out of four hydrogen nuclei. During this process, some matter was converted into energy, which was subsequently radiated out into the Universe. Over the course of time, this radiation would drive the formation of most biological and cultural complexity.

All stars came into being by gathering matter and energy from their surroundings through the action of gravity. Yet after their initial formation, harnessing external matter was no longer needed for their continued existence. In fact, stars shine thanks to the generation of energy within themselves (under the pressure of gravity) and not through a continuous extraction of matter from their environment. In contrast to living beings, which continuously have to extract both matter and energy from their surroundings in order to maintain their complexity, stars do not need any new matter in order to shine.

During the early period of galaxy formation, many huge stars formed that burned very quickly and subsequently exploded. This generated gigantic energy flows, which would have destroyed most, if not all, nearby higher levels of intermediate complexity that might have formed, such as planets or perhaps even life. In other words, a great deal of energy ultimately derived from the big bang was spent without creating any such complexity. Yet these explosions did create the right circumstances for higher chemical elements to form.

INCREASING COMPLEXITY OF THE ELEMENTARY BUILDING BLOCKS

During the early phase of galaxy development, stars consisted of only very few elements, mostly hydrogen and helium. This severely limited the level of complexity the early Universe could attain. Over the course of time, however, an increasing variety of building blocks came into being. This was the result of nucleosynthesis, the forging of new elements within stars. Stellar nuclear fusion processes gradually but inevitably leads to the depletion of the main fuel supply, hydrogen. In larger stars under the continuing impact of gravity, the core then heats up to temperatures higher than 10^8 Kelvin. New nuclear fusion processes begin, in which helium is converted into ever heavier chemical elements, up to iron. Also, this situation is a relatively stable steady state. In contrast to the circumstances prevailing right after the big bang, when expansion went so very quickly that the formation of heavier chemical elements was not possible, in stars approaching the end of their lives there is sufficient time for more complex atomic nuclei to form. As a result, these chemical elements are comparatively abundant.

After these processes are completed and no further nuclear fusion is possible within stellar cores, a star may first implode under the action of gravity and then explode as a result of sudden further nucleo-synthesis. During these short-lived yet very violent circumstances, even heavier chemical elements are formed, up to uranium. Since these circumstances last only a very short time, heavy chemical elements such as gold and uranium are rare. Over the course of time, these so-called nova and supernova events began seeding the surrounding space with these new forms of complexity. In other words, they enriched nature's construction kit with an increasingly large assortment of building blocks. As a result, more complex toys could be built. These chemical elements were sometimes dispersed to areas where the circumstances were favorable for the rise of further complexity. When close to the outer edges of galaxies new stars and planets formed from galactic dust clouds and assimilated these new chemical elements, new levels of complexity could emerge. On the surface of one such well-positioned planet, these chemical elements would become the essential building blocks for biological and, much later, for cultural complexity.

STARS AND PLANETS

Most complexity within stars exists thanks to the fact that there is a continuous supply of energy generated inside by fusing nuclei that are tightly packed under the action of gravity. This energy then flows down the energy gradient towards the surface. The complexity of stars is, therefore, the result of a balance between gravity and nuclear fusion. The situation for planets is more complicated. Their complexity is caused by gravity, by energy generated inside – mostly through nuclear fission under the effect of gravity – as well as by external energy received in the form of radiation from their central stars. This radiation mostly influences the planetary surfaces. Like stars, planets do not need to continuously extract new matter from their environment in order to exhibit certain levels of complexity.

Because of this comparatively simple situation, most stellar and planetary complexity is rather basic. In the words of Philip and Phylis Morrison: ‘Astronomy is thus the regime of the sphere; no such thing as a teacup the diameter of Jupiter is possible in our world’ (Morrison and Eames 1994: 7). In other words, in the physical Universe, spheres, and clusters of spheres, rule. Since most matter in the Universe rotates, the resulting centrifugal force causes these spheres to flatten. This explains why the sky is dominated by more or less flattened spheres or by constellations of such spheres in various shapes. Only comparatively small objects such as asteroids can attain more complex forms. Teacups were, however, the invention of culturally-endowed life forms.

Since stars and planets mostly rely on energy sources from within that ignite spontaneously and maintain themselves without any form of active control, the possibilities for complexity within such bodies are rather limited. Especially deep inside big spheres and at the centres of galaxies, the *free energy rate densities* may be small, but the temperatures and pressures are elevated. These circumstances do not allow for the rise of more complex matter regimes.

THE FORMATION OF COMPLEXITY AT THE EDGES

Near the edges of galaxies, or on the surfaces of stars and planets, higher levels of complexity can emerge. This is because the energy differentials between the surfaces of stars and planets and the surrounding space are large, while the energy levels may be more moderate. On the surfaces of stars, of course, the energy levels are still way too high for any great molecular complexity to exist. On the surfaces of small planets, by contrast, the energy levels may be more moderate. As a result, mountains and oceans can form, while chemical evolution might take place. In addition, the comparatively mild energy flow from a central star may significantly contribute to the rise of planetary complexity. Below the surfaces of planets towards the center, however, the chances for greater complexity are dimmer. Very soon, the energy levels become too high and the energy differentials too small. On planets, therefore, only the surfaces and atmospheres can exhibit significant complexity.

As a result, biological and cultural complexity are marginal phenomena. They can only exist on the outer edges of planets circling stars which, more likely than not, find themselves on the outer edges of galaxies. Only in such places are the conditions right. The energy flows and levels are neither too big, which would destroy the higher forms of complexity, nor too small, which would not allow their formation.

WHY IS THE EARTH SUCH A GOOD PLACE FOR HIGHER COMPLEXITY?

First of all, the Earth has more or less the right size. If the Earth were smaller, its weak gravity could not retain its atmosphere or liquid surface water; if the Earth were bigger, its resulting gravity would crush most living things, especially on land or in the air. Also, as a result of its size, the Earth's interior is still hot. This provides energy for the process of plate tectonics, which recycles most of the Earth's surface, including waste produced by life (Westbroek 1992).

In the second place, our home planet orbits the Sun at more or less the right distance. This means that solar radiation is neither too weak, in which case that it would not provide enough energy for life to flourish, nor too strong, in which case that it would destroy life. In the third place, the Earth is endowed with a large moon which stabilizes the rotation of the Earth's axis. Without this moon, the obliquity of the Earth's axis would change erratically. This would have produced huge changes in solar radiation on the Earth's surface, which, in its turn, would have made it far more difficult, if not impossible, for complex life to develop (McSween 1997: 119). Also, the orbits and sizes of the other planets, most notably Jupiter, would have contributed to keeping the terrestrial conditions right for the emergence of ourselves and of other forms of complex life.

Today, all terrestrial life flourishes within a rather small bandwidth of energy levels. Temperatures range between zero to ninety degrees Celsius, while pressures vary from 1070 atmospheres (Marianas Trench) to about 0.6 atmospheres in high mountains or in the air itself. To be sure, bacterial spores may be able to survive lower temperatures, yet they cannot multiply in such circumstances. From the terrestrial point of view, this may appear to be a rather wide bandwidth. Yet seen from the perspective of big history, this is a rather special situation. Only on the surfaces of planets, or of moons circling large planets, may we find such conditions. On our home planet, this delicate equilibrium of energy flows and levels consists of solar radiation falling onto the surface of our planet, heat generated from the Earth's interior, and the loss of heat through infrared radiation back into the cosmic trash can. Thanks to this finely tuned balance of energy levels and flows, life could emerge.

LIFE AND ENERGY

Although life is very small compared to planets, stars or galaxies, surprisingly, perhaps, it has succeeded in generating far higher *free energy rate densities* (Chaisson 2001: 139). The average Φm of our galaxy would be only 0.5 erg/s/g, while our Sun's Φm amounts to about 2 erg/s/g. The Earth's Φm is considerably higher, namely 75 erg/s/g. Yet modern plants manage to handle about 900 erg/s/g, while animals do even better (20,000 erg/s/g). How is it possible that the huge amounts of energy produced in stars lead to such low Φm values? There are two reasons for this: first, stars are very heavy, and, second, the energy flows are not that large. In absolute terms, the energy flows generated by life are, of course, minute. But, because life is very small and the energy flows it generates are large by comparison, its resulting *free energy rate densities* are far higher. The same is true for the entropy produced by life, especially the low level radiation, which can easily be discharged in the cosmic trash can.

The emergence of life implied the rise of a fundamentally new mechanism for achieving complexity. Unlike stars and galaxies, biological regimes do not thrive because they convert matter into energy within themselves from existing supplies. Life needs to continuously tap matter and energy flows from its surroundings in order to maintain itself and, if possible, reproduce (Lehninger 1975: 3–4). If living creatures were not to do so, they would very soon die and disintegrate. This is not a new insight. Already in 1895, the Austrian physicist Ludwig Boltzmann stated that all life is a struggle for free energy (quoted in White 1959: 34). Many academics have followed in Boltzmann's footsteps (for an overview, see White 1959: 34 ff).

Unlike stars, living cells extract matter and energy from their environment and rework them at very moderate temperatures and pressures, while utilizing very complex molecular machinery. In addition, all the biochemical compounds produced by cells can be said to fulfil functions for either their own survival and/or for the survival of the entire organism. These are major differences between physical and biological complexity. All living organisms survive by using hereditary information, with the aid of which they program themselves. I therefore propose to define life as ‘a regime that contains a hereditary program for defining and directing molecular mechanisms that actively extract matter and energy from the environment, which matter and energy is converted into building blocks for its own maintenance and, if possible, reproduction’.

THE RISE OF LIFE

We do not know how and when life first formed. Claims for the earliest evidence for life dating back to about 3.8 billion years have recently been challenged. Firm evidence for terrestrial life is about 3 billion years old. Given the fact that the Earth was formed some 4.8 billion years ago, there may, or may not, have been a long period of physical and chemical evolution leading to the rise of early life. Neither do we know whether life actually formed spontaneously on the Earth, or whether it was transported to us from elsewhere by whatever celestial object happened to dive into our atmosphere. If life did originate elsewhere in the Universe, we do not know where, when and how this happened.

If life originated on our home planet, more likely than not it was preceded by a long process of increasing physical complexity on the Earth's surface. This process is usually called chemical evolution. Under the influence of energy flows such as sunlight, volcanic activity, lightning and perhaps radioactive decay, increasingly complex molecules would have formed. At a certain point in time, a spontaneous process of self-organization leading to life would have kicked in. Next, Darwin's mechanism of natural selection would have started acting as a filter, allowing fitter organisms to produce more, and/or more efficient, offspring than others. This produced a selection for organisms that became both increasingly better at tapping matter and energy flows from their environment and at preventing themselves from becoming sources of matter and energy for others.

Early life may well have fed on the products resulting from chemical evolution. For a while, this would have provided enough matter and energy to survive and, if possible, reproduce. Yet after a certain period of time, life would have consumed more chemical soup than was formed anew. In the long run, therefore, chemical evolution could not possibly have sustained life. The earliest living blobs may also have extracted matter and energy from underwater volcanoes, the so-called black smokers. Such situations can be found today and may well have existed throughout the history of life on the Earth. And, as long as black smokers kept smoking and as long as no major mishaps took place, the continuity of life in such locations was assured.

Ever since the origin of life, the presence of sufficient water has been an absolute requirement for its continued existence. Without it, the matter and energy flows needed for life's sustenance could not have existed. Up until today, the distribution of water on our planet has set the boundary conditions for the areas where life and culture can develop. This suggests that life originated in the oceans, especially since the overall salt concentration within cells is very similar to that of the modern oceans (and, more likely than not, that of the ancient oceans also). In those early circumstances, the salt concentration of the pioneer cells could not have been very different, for that would have generated elevated energy differentials which would have destroyed those early cells almost immediately. Over the course of time, especially after life moved out of the seas onto land, such energy differentials did develop. As a result, mechanisms had to be evolved to protect cells against this new and hostile environment.

Early life forms were comparatively simple and could, therefore, handle only comparatively gentle energy flows. Yet these organisms must also have been pretty robust, because they were able to live under conditions of far higher external energy levels and flows than the ones which prevail in most places where life thrives today. Temperatures were higher; radioactivity and volcanism were far more prevalent than nowadays. Moreover, the Earth was bombarded by meteorites of many different sizes. Clearly, early life must have been adapted to these circumstances from the very beginning.

INCREASING COMPLEXITY

Living organisms are regimes which maintain a relatively stable steady state. This comparative stability over billions of years allowed sufficient time for many types of higher complexity to form both within and among cells. Not unlike the building blocks of most physical regimes, the basic construction kit of life consists mostly of spheres, the cells. This is not the result of gravity but of the fact that the molecules which make up the skins of cells attract one another and as a result cause surface tension. Since gravity does not play a major role in the formation and sustenance of cells, their interiors could become very complex.

At a certain point in evolution, some cells began to cooperate in harnessing matter and energy. Some of these cells may have adapted to others to the extent that they became mutually dependent yet remained biologically separate. This inter-species division of labour is perhaps the most common form. Other cells may have fused into larger complexes, which led to forms of intra-cellular division of labour. Such cells may have emerged about two billion years ago. Over the course of time, this led to the emergence of even more complex eukaryotic cells, which could handle far greater matter and energy flows than their more humble cousins, the prokaryotic organisms.

In eukaryotic cells, the nucleus serves as the hereditary storehouse. Organelles such as mitochondria specialize in energy metabolism, while chloroplasts devote themselves to capturing sunlight and converting it into energy. Because eukaryotic cells became more versatile as a result of this intra-cellular division of labour, they became the building blocks for all higher biological complexity. Yet many organisms remained small and comparatively simple. These are micro-organisms we know today. As a result, the tree of life differentiated into increasing numbers and shapes.

Another way of achieving higher complexity consisted in increasing the cooperation among cells with the same genetic make-up. At a certain point in time, such cells began to hang together. Both prokaryotic and eukaryotic cells were able to do this. But over the course of time, only eukaryotic cells learned how to cooperate and divide tasks. I call this latter process the inter-cellular division of labour. As a result of the inter-cellular division of labour, cells within one single organism began to differentiate. This allowed for higher levels of complexity. The selective force that drove such processes consisted of the new opportunities this division of labor offered to improve the extraction, and use, of matter and energy. As a consequence, ever more new life forms began to emerge with increasingly intricate shapes. Gravity, however, still sets the upper limits on the size and shape of life forms. It is no coincidence that the biggest living bodies developed in the oceans, where buoyancy and gravity balanced one another to a considerable extent.

Here we see a major difference between the differentiation of biological regimes and of physical regimes. All more complex life forms exhibit a clear differentiation of both forms and functions within their own regimes. Physical regimes, by contrast, do show a differentiation of forms but not of functions. Galaxies, for instance, consist of a great many different objects. But to say that all the stars and whatever objects galaxies consist of actively fulfil functions for one another in order for the galaxy to exist and thrive does not make any sense to me.

We do not know how stable micro-organisms are in an evolutionary sense. There are some hints of great stability. In the shallow waters off the Western Australian coast, for instance, the so-called stromatolites may have existed for about three billion years. Stromatolites are basically mounds of micro-organisms that cluster together. Single cells living in the oceans may well have been rather resistant to change also, because their environment would have not have altered a great deal during the past three billion years or so. In other words: comparatively stable matter and energy flows in the environment may well have caused comparatively little evolutionary change.

Yet evolution by chance, caused by random variations in the genetic program which proved to be advantageous in terms of survival – or at least not disadvantageous – has led to an ever-growing range of organisms, especially when the environment changed. In actual fact, the process of evolution itself has also changed the environment which, in its turn, would have stimulated the emergence of new species. This led to feedback loops that might well have speeded up evolution. As a rule, the more energy a species could extract from the environment, the more complex it became, and vice versa.

TAPPING NEW ENERGY FLOWS

Over the course of time, life has succeeded in maintaining itself and spreading all over the world, including too many places that did not offer a free chemical lunch. This could happen because micro-organisms and later plants evolved that were able to exploit sunlight. This energy was used for combining the atoms of carbon dioxide and water into a great many organic substances, which became the building blocks of life. We do not know how life learned to exploit sunlight for its own purposes. But, surely, mastering this art laid the foundation for all further biological complexity.

In this process called photosynthesis, free oxygen is released. It may have taken two billion years, but eventually this led to an oxygen-rich atmosphere. Subsequently, through respiration the internal combustion of organic matter with the aid of atmospheric oxygen became the major energy source for animals. Over the course of time, photosynthesis would, therefore, provide most of the energy that drove biological evolution. The oxygen-rich atmosphere allowed for the formation of the stratospheric ozone layer, which started to protect life against ultraviolet radiation. Up until that time, the energy flow of sunlight had suppressed the rise of biological complexity on land. Now, for the first time, life could leave the cradle of its protective watery surroundings and begin to colonize the entire planet.

The rise of an oxygen-rich atmosphere created another new type of energy differential. First of all, it provided energy for organisms that did not participate in the process of photosynthesis, both in the water and on land. But, perhaps even more importantly, it made possible the emergence of ever larger and more complex multi-cellular complexes. This was the case because oxygen could be transported to cells that were not in direct contact with the outside world. They could thus share in the exploitation of energy differentials. All the organisms that could not cope with the rise of the oxygen-rich atmosphere and the associated rise of energy differentials had two options. The first one was to limit themselves to places where the oxygen concentration remained low enough to handle. The second option was to become extinct.

The general trend seems clear: the more intricate biological regimes became, the greater the matter and energy flows were that they could tap. Apparently, over the course of time, biological evolution has created structures so intricate that they can handle increasingly larger matter and energy flows, at least for a time, without being destroyed by them (Christian, pers. com., 2003). The price to be paid for greater complexity was a growing vulnerability when the conditions changed. The huge matter and energy flows caused by volcanic eruptions and the impacts of extraterrestrial objects especially could spell the end of more complex organisms. In such circumstances, their less complex fellows appear to have had better survival chances. As a consequence, the life span of the more complex species as a whole decreased. In other words, the more complex species became, the quicker they became extinct. The overall result was the emergence of growing numbers of short-lived species exhibiting ever higher levels of complexity.

THE CAMBRIAN EXPLOSION OF LIFE

About 550 million years ago, the above developments led to the so-called Cambrian explosion of complex life forms. A great variety of multi-cellular complexes suddenly emerged, endowed with an ever greater variety of organs, all of which began to fulfil functions for one another to make it easier for the whole to survive and thrive. This led to the types of complex living organisms we are familiar with today.

The Cambrian explosion of life may have been caused by sudden changes of energy flows and levels on the Earth's surface. It seems that right before the Cambrian era, the Earth's surface had frozen over almost completely. This would have severely restricted the room for terrestrial life and may have wiped out many individuals and perhaps entire species. When for reasons yet unknown the big thaw began, suddenly a huge new niche opened up for the lucky survivors and their offspring (Walker 2003).

During the Cambrian explosion of life, two general types of complex organisms came into being that have continued to exist up until today. On the one hand, there are the ancestors of modern plants. They extract their energy from sunlight and their chemical elements from soil or water. With some exceptions, such organisms do not eat other organisms. Since they do not need to move and catch prey, they lack brains. Some parts of plants are actively involved in extracting energy. They tend to position themselves in ways that are the most favorable for capturing the right amount of sunlight. For the same goal, their photosynthetic mechanisms as well as their production of pigments are continuously fine tuned. According to Eric Chaisson, modern plants handle *free energy rate densities* of about 900 erg/s/g (2001: 139).

On the other hand, there are animals. These are basically species feeding on other organisms. For the lucky ones, this implies the appropriation for their own purposes of supplies of energy and matter gathered by other creatures. The eaters use this energy constructively for themselves. Yet they became increasingly destructive for the unlucky ones that were eaten. During the process of evolution, therefore, living species became both increasingly constructive and destructive.

Since animals need to eat plants and/or other animals, they developed ways of purposefully moving around, including brains. They needed weapons to defeat their prey and suitable digestive tracts in order to eat them. As part of this process, animals became better at extracting both matter and energy. This meant that their *free energy rate densities* should be much higher. And, sure enough, according to Eric Chaisson, the *free energy rate densities* of modern animals would be in the order of 20,000 erg/s/g (2001: 139). As a result, animals also became greater potential sources of matter and energy for others. In order to survive, they needed to develop ever better ways of defending themselves. Plants also began to defend themselves against predators, for instance, by producing toxins. The overall result was an increasingly complex biological regime consisting of ever more and more different species. Within this constantly changing regime, an increasing variety of matter and energy flows was exploited. This constant search for sufficient matter and energy in order to survive and thrive has been the major factor that has driven biological evolution up until today.

The development of a biological waste disposal regime must have been an absolute precondition for the continued existence of life on this planet. Without it, life would have choked in its own dirt a long time ago. One may wonder whether the rise of a biological waste disposal regime was an almost inevitable component of the successful evolution of life on our planet. It is not inconceivable that elsewhere in the Universe, life got kick started only to find itself being drowned by its own waste. Here we see another great difference with physical regimes. Although the Universe as a whole does function as a huge entropy trash can, galaxies, stars or planets have never evolved such garbage solutions of their own.

BRAINY ANIMALS

It is no coincidence that animals which possessed the characteristics of both plant eaters and predators developed the biggest and most complex brains so far and came to dominate the world. For humans could exploit the matter and energy flows provided by both plants and animals. The secret of human success has been a brain that could facilitate communication, coordination and adaptation of their behaviour, including the use of tools, to an unprecedented extent. The specific development of the human brain may have been the result of many, perhaps unrelated, geological and biological changes, yet the evolutionary trend is clear – towards species with bigger and more complex brains which allowed them to better tap matter and energy flows.

In the animal kingdom, the human brain is the most complex of all, and it uses a great deal of energy. Magistretti *et al.* (2000) calculated that 'although the brain represents only 2 % of the body weight, it receives 15 % of the cardiac output, 20 % of total body oxygen consumption, and 25 % of total body glucose utilization'. According to Eric Chaisson (2001: 139), while the average *free energy rate density* of human bodies is about 20,000 erg/s/g, the *free energy rate density* of the human brain amounts to a whopping 150,000 erg/s/g. This rather prodigious consumption must have had an upside. Natural selection would only have allowed the human brain to develop if it had made it easier for our ancestors to extract sufficient matter and energy to survive and, if possible, reproduce. And multiply they did, notwithstanding the fact that humans did not possess any other major biological weapons such as horns, hooves or venom. So far, the energy harnessed by using bigger and more complex brains has clearly outweighed the greater consumption of energy needed to keep the brains going.

Brains run complex software that can, at least in principle, be adapted according to the circumstances. This makes brainy animals far more adaptable, and therefore more effective, than living species which are not so well endowed. In the social sciences, this software is called *culture*. By using their cultural software, enhanced by ever more intricate forms of communication, humans have increasingly both adapted themselves to their environment and the environment to themselves. The sociologist Norbert Elias (1978) and the world historian William H. McNeill (1991, 1992: VII–XIII), among others, have made this point. More recently, David Christian characterized this process with the term *collective learning*. In Christian's view, collective learning operates for humans in ways similar to how natural selection works for the rest of nature (2004a, 2004b).

CULTURE AND ENERGY

According to the view pursued here, cultural regimes are collective responses to the problems that people face. Yet one may wonder whether there is a bottom line to this problem-solving. Based on Leslie White's approach to culture as a way of capturing more energy, the Canadian ecologist Vaclav Smil summarized culture as follows:

> From the perspective of natural science, both prehistoric human evolution and the course of history may be seen fundamentally as the quest for controlling greater energy stores and flows (1994: 1).

This approach may not be popular among social scientists. Surely, human behaviour is far more complex and varied than just harnessing energy. I would not deny that. But, following Leslie White, Marvin Harris, Jeremy Rifkin, Vaclav Smil and David Christian, among others, I argue that for most, if not all of human history, the quest for sufficient matter and energy to survive and, if possible, reproduce has been the overriding theme. And the reason that humans have been able to harness ever larger matter and energy flows is to be found in their culturally learned behaviour. The matter and energy flows that our species has sought to master had to be neither too large, because humans would have succumbed to their effects, nor too small, because they would not have supported human life sufficiently. As I have argued, this is not only true for human history but also for big history as a whole.

All human efforts to capture matter and energy flows have inevitably generated entropy. While the low level radiation produced by human activities could comparatively easily be radiated out into the cosmic trash can, for matter flows this was not the case. As a result of the ongoing human activities, therefore, material entropy on the surface of the Earth has relentlessly increased.

THE EMERGENCE OF EARLY HUMANS

Around three to four million years ago, the first early humans emerged in a landscape in which the energy levels were characterized by a rather narrow bandwidth. The East African savannas have a rather mild climate. All year round temperatures would have ranged between twenty and thirty degrees Celsius. This does not differ a great deal from the average human body temperature. As a result, the early humans did not need extensive protection against high or low temperatures. Also, the air pressure on the East African savannas is rather mild, on average about 0.9 atmospheres. In this situation, the early humans would have been able to keep a *free energy rate density* of about 20,000 erg/s/g going (Cook 1971: 136)[6].

The oldest utensils made by human hands that can be clearly recognized as such date back to around 2.5 million years ago. Apparently, by that time early humans had found ways to increase their matter and energy flows with the possibilities their hands offered, including the development of an opposable thumb, which allowed far greater dexterity than before. Subsequently, natural selection for traits stepping up the harvesting of matter and energy (including defence and offence) may have led to the emergence of all-round hands suited for performing a great many different tasks, including the making and use of tools.

According to the late Dutch astronomer Anton Pannekoek (1953), tool-making and tool-use may well have led to the simultaneous development of language and thought. This would have favoured selection for bigger and more complex brains, which, in their turn, would have facilitated better tool-making and tool-use. Over the course of time, this feedback process would have allowed the early humans to harness increasing amounts of matter and energy. It may, therefore, not be coincidental that about only 500,000 years after the earliest known tools were made, two new human species with far bigger, and presumably also more complex, brains emerged in Africa, first *Homo habilis* (handy man), and a little later also *Homo erectus* (upright man).

FIRE CONTROL

While both these new human species used tools, *Homo erectus* also began to use fire. *Homo erectus* was also the first human species to leave Africa and spread to many places on the Eurasian continent. They learned to adapt to many different climatic zones, with temperatures ranging from minus 20 degrees Celsius to plus 50 degrees Celsius. In all these circumstances they managed to extract sufficient matter and energy flows to survive and reproduce for at least 1.5 million years. Early fire control allowed humans to intentionally burn the landscape in order to favour certain plant species and diminish the survival chances of others. Predators could be kept at greater distances. Fire control also facilitated big game hunting and the clearing of woods in order to provide pasture for game animals. Thus, through fire control humans may have changed the face of the Earth for a long time. In doing so, they may have influenced the biological and inanimate planetary regimes for an unknown period and to an unfathomable extent. Slowly but surely, as the hunted became hunters, a growing power difference between the early humans and other higher animals developed to the advantage of the ancient folk (Gamble 1995: 66–70; Goudsblom 1992, Pyne 2001). Instead of being mostly scavengers, humans became hunters. Through cooking, roasting and other comparable types of food preparation, humans gained access to a greater range of foodstuffs, and thus to new sources of matter and energy.

Just like life forms and Gaia had done before, the early humans began to create their own micro-climates that were favourable to the protection of their own complexity (and, unintentionally, also the complexity of some unwanted other species) more so than any other species before. All this signalled the beginning of a long process in which humans began to adapt the planetary environment according to their own desires and designs. In particular, modern humans, *Homo sapiens*, who may have emerged around 200,000 years ago, began to migrate to virtually all parts of the globe (the poles excepted). This was an unprecedented achievement, if one thinks of humans as animals, partly because of the range of environments in which humans learned to live, and partly in terms of the speed of the process. It meant that humans began to harness matter and energy in almost the entire inhabitable world, including the high mountains, where the air pressure was no higher than only 0.6 atmospheres. According to recalculated data from Cook (1971: 136), more recent gatherer-hunters would have handled *free energy rate* *densities* of about 50,000 erg/s/g. This would have been mainly due to fire control. And as a result of human population growth, the total human use of matter and energy flows went up accordingly.

It is not clear to what extent this increase in *free energy rate density* would have led to any more food intake. It may well be that most of it was used for creating, or destroying, complexity beyond the human body. This was the beginning of a new trend, namely humans using ever larger energy flows to create or destroy external complexity. Ever since that time, this trend has continued to exist. This makes the use of *free energy rate densities* for human history more problematic, since Φm only refers to human bodily weight and not to the external mass that underwent the energy flows handled by humans. Obviously, humans have never managed to live for a long time with daily energy intakes higher than 4000 to 5000 kcal, which corresponds to about 40,000 to 50,000 erg/s/g. Any substantially higher levels of energy consumed by humans could not possibly have flown through their bodies without destroying them. As a result, all the further increases in energy flows handled by humans must have flowed through external matter. Since I do not have estimates at my disposal of how large such external masses would have been, reliable corrections are not yet feasible. All the *free energy rate densities* for human history presented below must, therefore, be viewed with due caution. I view them first of all as indicating major trends and not as the last word on energy flows.

It is not very clear to what extent the matter and energy flows harnessed by early humans were sometimes too big or too small. It may well have happened that early humans occasionally started fires that went out of control and killed them. They may also have settled in places where, as a result of human exploitation or because of climate change or natural disasters, the extractable resources became too scarce for the early folk to survive. This may be very hard, if not impossible, to glean from the fossil record, which is very limited anyway.

The rise of modern humans may have led to the decrease in ecological complexity. First of all, the sustained burning of savannas and forests must have changed their biological composition. As a result, some species may have become extinct, while other species profited. It is unknown to me whether human fire control led to the emergence of any new species. Modern humans may well have exterminated a number of large animals, especially in those areas that had never been visited before, such as Australia and the Americas. Right now, it is not very clear whether climate change and/or diseases were also among the root causes of such extinctions. Yet it remains striking that only a few thousand years after humans moved into such new territories, most of these big beasts disappeared from the surface of the Earth. If true, this would represent an example of the decline of ecological complexity as a result of human action.

Up until 10,000 years ago, it does not seem as if humans brought about any great increase of material entropy. They were operating within the ecological web of the biosphere, and they did not accumulate any significant long-lasting material culture nor produce a great deal of long-lasting waste.

THE DOMESTICATION OF PLANTS AND ANIMALS

Curiously, the growing dexterity of human, as well as their capacity for communication, learning and remembering things, did not immediately produce any major changes in the ways *Homo sapiens* harvested its matter and energy flows. To be sure, between 200,000 BP and 10,000 BP, modern humans intensified production, yet they did not revolutionize it. Apparently, the capacity for culture, or collective learning, was a most important precondition for the domestication of plants and animals, but it was not its direct root cause. Around 10,000 years ago, however, our ancestors discovered new ways of extracting matter and energy from the environment. Slowly but surely, they began to gain control over the reproduction of plants and animals considered useful. As a result, humans could increasingly harness and manipulate the energy and matter flowing through the biological food chains. This signalled the beginning of the second great ecological regime transformation: agrarianization.

As we saw earlier, according to recalculated data from Cook (1971: 136) gatherer-hunters mobilized *free energy rate densities* of around 50,000 erg/s/g. Early agriculturists, by contrast, would handle around 160,000 erg/s/g. More advanced farmers and herders would do even better. They employed more than 260,000 erg/s/g. This was a fivefold increase. This does not mean that agriculturists ate more, or better, than gatherers and hunters. Over the course of time, quite often the opposite appears to have happened. The increasing *free energy rate densities* of agriculturists point to the fact that these people handled larger energy flows in order to produce sufficient food and other material means they needed.

The circumstances in which agriculture could thrive were more circumscribed than those in which gatherers and hunters operated. Although the pressure and temperature ranges were probably rather similar, a sufficient water supply was far more critical. As a result, even today agriculture has not spread across the globe's landmass as far and wide as gathering and hunting had done before. Also, the cultivation of fish in the seas and oceans has been taking off only very recently. This is mostly due to the problem of how to control fish stocks, while, until recently, catches were often bountiful.

There has been an extensive academic discussion over where and how the agrarian revolution took place[7]. Yet even today, the causes behind this great transition are not well understood. Both climate change – the end of the last ice age – and growing population pressure appear to have contributed to the emergence of the agrarian way of life. But, whatever the precise causes may have been, the effects are clear. The more efficient food production allowed increasing numbers of people to survive and, if possible, reproduce. And so they did, in all places where the agrarian regime took root. In other words, most new matter and energy were converted into growing numbers of people. As a result, a self-generated dynamics evolved, which led to a steady expansion of the agrarian regime to all suitable places (White 1959: 45–57).

Over the course of time, this led to a decrease in the matter and energy the remaining wild plants and animals could harness. They were increasingly marginalized or even became extinct. And since agrarian societies harnessed more intensive matter and energy flows, they proved dominant over the ancient gatherer-hunter regime. Just like the undomesticated plants and animals, this earlier human regime was also pushed back to places where farmers and herders could not, or would not, go. Today, all true gatherer-hunter regimes have completely disappeared.

Although agrarian societies became far more efficient in harvesting matter and energy flows than gatherers and hunters, this did not necessarily mean that all members of the band were better off. As a result, it may well be that, over the course of time, the average peasant had access to fewer calories than his ancestors during the age of gathering and hunting. As part of agrarian regime, people began to make an increasing variety of things, including better houses, storage areas, ceramics, forms of art, and monumental graves, with shapes that had not existed before during the known history of the Universe. In other words, the age of the teacup had begun. Many, if not all of these new shapes had the same general aim: the preservation of forms of complexity humans deemed desirable. As a result, the early folk began to produce more entropy also.

There are some striking parallels between the rise of complex animals in biological evolution and this phase of human history. The increasing interdependence of the cells of which multi-cellular organisms are constructed, as well as their inter-cellular division of labour, was paralleled by the growing human interdependencies and human social division of labour. In both cases, the resulting increased harnessing of matter and energy flows made those involved both more constructive and more destructive. The other parallel is that, while the speed of both biological and human innovations increased, the life spans of both the living species and the human cultural regimes involved decreased.

EARLY STATE FORMATION

The transformation into an agrarian regime led to social change. Because people became more tied to the land they worked, they began to live closer together and in greater numbers than ever before. This led to an increasing social division of labour. Yet these societies, which were largely based on kinship, remained comparatively egalitarian. To be sure, over the course of time agrarian societies became more hierarchical. Yet as long as there was enough room to move, no powerful group could impose itself upon others for long.

After about five thousand years, however, the agrarian revolution led to a most important social regime transformation: the emergence of states. In its barest essence, states are social regimes the elite of which has succeeded in monopolizing the important means of violence, at least to the extent that they are able to dominate the state. In the final analysis, this meant harnessing important matter and energy flows and denying them to others. This inevitably involved taxation: the channelling of matter and energy flows generated by others. Early state formation meant that for the first time in history, humans began to systematically exploit other humans as matter and energy sources. In the centres of early states this led to increasing cultural complexity, while independent local forms of complexity declined.

Robert Carneiro (1970) pointed out that all early states emerged in ecologically circumscribed geographic situations: usually fertile river valleys surrounded by dry areas, mostly deserts. In other words, these were regions where the harvesting of matter and energy flows was comparatively easy, while they were flanked by areas with only very limited opportunities for doing so. This situation allowed the people who succeeded in manipulating larger matter and energy flows to dominate their weaker fellows. As a result of the growing inequality and the concomitant social division of labour, the matter and energy flows within and among societies became increasingly complex. This is not the place to go into any detail, but, in general terms, it seems clear that the new social regimes were first and foremost dealing with the questions of who would perform the tasks of matter and energy extraction; its elaboration and preservation; and, last but not least, who would have access to the results of all this labour. As was the case with biological evolution, there were a few basic strategies for doing this:

using disinformation, stealing, and using force. In all likelihood, all these things would have happened during all stages of human history. Yet during the period of state formation this became more apparent and organized. Since that time, humanity has expended a great deal of energy on pursuing these strategies and on countering them.

All this required new ways of safeguarding information. Up until that time, most cultural information had been stored in individual brains. With the rise of the early states, however, humans invented systematic regimes for recording information by material means, ranging from clay tablets to woollen cords. This allowed them to increasingly harness matter and energy flows. The art of writing allowed, in fact, a more efficient use of both information and disinformation. Since, for the powerful strata, control over the information flows became increasingly important, huge efforts were expended to make sure that they were used in their own interests, while access was denied to others. This included limiting such information flows to privileged and often tightly controlled professional groups, the use of secret codes, and public displays of propaganda. Although it took a long time, the dissemination of the art of writing worldwide was inevitable. In our time, mostly as a result of the rise of worldwide electronic communication, we have witnessed a new explosion in the importance of externalized information and its associated uses for both information and disinformation.

Since states were getting bigger and more complex, their inhabitants did not know all the others face to face any longer. In order to keep the state together, the rulers had to expend a great deal of energy on forging overarching identities, first with the aid of the emerging state religions, and later by using state bureaucracies including schools. Benedict Anderson calls the results of such efforts ‘imagined communities’ (1991). In most early states, such overarching identities were usually expressed in terms of symbolic kinship, with gods, kings and queens often portrayed as the ‘fathers and mothers’ of their people.

Some new matter and energy flows were used for constructing the first large buildings, essentially huge artificial hills, most notably pyramids. In order to build them, human and perhaps animal muscle power was used to defy gravity and produce the first architecture of power. Since that time, humans have continued to make such things. While the more recent constructions have perhaps become more intricate, for a long time they did not become much taller. Only during the industrial period did it become possible to construct buildings that grew in height once again. Yet the biggest gains were made during early state formation and not in recent times. This was the result of the limits gravity poses for such human endeavours. The shapes of smaller artificial objects (such as teacups) were, of course, less constrained by gravity. As a result, they could exhibit a far greater variation.

State formation was not an ecological regime transformation. No new techniques were pioneered that would revolutionize the extraction of matter and energy from the surrounding environment. Certainly, inventions were made, some more important than others, most notably the increasing exploitation of energy flows from wind and water – both derived from solar energy. In some areas, people began mining coal and other combustible substances. Yet up until the Industrial Revolution, the ways in which people extracted matter and energy from the environment and used it for productive purposes in fact changed little.

The techniques that facilitated the extraction of matter and energy from other people, by contrast, most notably arms and armies, underwent revolutionary change. A new dynamics of growing social competition had begun, which led to the growth and expansion of states at the expense of independent farmers, herders and gatherer-hunters. It took about five thousand years before the process would be (almost) completed, yet this was the way states began to spread all across the world. To be sure, for a long time, tribal societies with sufficient destructive power – the Mongols offer probably the clearest example – could still overpower some states. But, in order to stay in power, the invaders could not maintain both their tribal status and their dominance over state societies for long. If the conquerors wished to consolidate their power, they had to adopt the lifestyles of the complex societies they had conquered.

GLOBALIZATION

In my view, globalization is the emergence of a worldwide division of labour. Globalization is therefore a social regime transformation. This global division of labour was created by people who could be described as belonging to the middle classes. In contrast to traditional elites and peasants, these emerging middle classes were not tied to the land. As a result, they could only increase their matter and energy flows through trade, production and conquest. About five hundred years ago, some emerging middle classes succeeded in escaping from the control of their traditional rulers. Over the course of time, they were able to take over state control, first in the Seven United Provinces, next in parts of the British North American colonies, and subsequently elsewhere in the Americas and Europe. Especially since the beginning of the nineteenth century, because of the Industrial Revolution and the resulting emergence of middle classes worldwide, this process has gained momentum all around the globe.

The first wave of globalization began after Europeans had learned to exploit the energy stored in winds and ocean currents to transport themselves and their cargo all around the world. For the first time in human history, people began circling the globe within their own lifetime. Europeans began to sail the Seven Seas on ships armed with heavy guns looking for profit wherever it could be found. Soon, this led to a struggle for dominance between Spain, Portugal, Great Britain and the Seven United Provinces in the Americas, Asia and the Pacific area. As a consequence, these three great world zones merged into one single global entity increasingly dominated by Western Europe.

Especially after large portions of the Americas had been forcibly integrated into the growing world economy and direct trade links all over the world had been established by both peaceful and military means, a global social division of labour began to take shape. This led to a further intensification of the matter and energy flows. As a result, global cultural complexity began to rise. Local forms of complexity, by contrast, were often overwhelmed by these new matter and energy flows and succumbed or became marginalized.

After Europeans had become firmly established along the Atlantic seaboard of North America and were no longer dependent on matter or energy flows from Europe, a considerable number of them succeeded in getting rid of their colonial masters. They declared themselves independent from Britain and formed the United States of America. This new state was controlled by the wealthier members of society, both landlords and people belonging to the middle classes. The French revolution, in its turn, found great inspiration in this liberation movement on the other side of the Atlantic Ocean. This set the tone for societal shifts all over Europe. Yet arguably, the greatest shift took place in the Spanish and Portuguese Americas. The French occupation of the Iberian Peninsula had weakened Spanish and Portuguese control to such an extent that the emerging Central and South American middle classes could get rid of their colonial masters. Unfortunately for them, however, they soon found themselves in the grip of the local landholding elites. As a result, even today the Latin American middle classes are still struggling to get free from that grip.

INDUSTRIALIZATION

The third great ecological transformation, industrialization, greatly reinforced these trends, owing to the fact that it was based on fundamentally new ways of tapping energy sources for productive uses. Until that time, all machines had been driven either by human and animal muscle power or by wind and water energy. These were all renewable energy sources. The harnessing of fossil fuels for productive purposes, however, first coal and later oil and gas, implied fundamentally new ways of handling matter and energy flows. Industrialization was, therefore, a major ecological regime transformation. As a result, huge power differences within and among societies developed. In industrializing societies, nationwide cultural complexity rose once again, while many forms of local complexity declined. In the rest of the world, cultural change as a result of industrialization proved inevitable also.

According to recalculated data from Cook (1971: 136), the early industrial societies would have handled on average *a free en-*

ergy rate density of about 770,000 erg/s/g. Today, by contrast, more advanced technological societies may command about two million erg/s/g or more. Again, this means that, although such people may eat more than ever before, most of the increase is due to external energy flows. Industrial societies emerged in temperate zones with temperatures ranging between minus 20 to plus 30 degrees Celsius. The air pressure was close to one atmosphere, while there were always abundant water supplies. Although since that time many industrial production processes have moved to places where temperatures can be higher, interestingly the other conditions have not changed a great deal yet. Today, there are very few industries in high mountainous areas or in regions lacking sufficient water. In other words, the spread of industrial life across the globe has been even more limited than the spread of agriculture (which, in its turn, had been more limited than gathering and hunting). And, while risking to state the obvious, in contrast to gathering-hunting and domestication of plants and animals, industry has not yet taken off in seas or oceans.

Let us return to the early rise of industrialization. Control over the new production processes allowed the middle classes to become the most wealthy and powerful stratum of society. This was, in fact, Marx's observation of the bourgeoisie taking over the state. In order to gain state control, the middle classes began to campaign for voting rights for the wealthier portion of society. Later, the emerging working classes succeeded in organizing themselves to the extent that they could also gain access to democracy. These societal shifts led to the emergence of democracies we are now familiar with. This process is now spreading around the world for exactly the same reason, the rise of middle classes worldwide.

Since access to the new matter and energy flows was initially very unequally divided, huge worldwide power differences evolved. As part of this process, the industrializing nations began colonizing large parts of the world. After almost all the conquerable world had been subjugated, the newly industrialized nations battled it out among themselves. This led to two world wars. Yet over the course of time, all the areas which successfully industrialized became wealthy to an extent unparalleled in human history, first the elites and later also sizable portions of the general populace. Apparently, the elites found it impossible to keep the new matter and energy flows to themselves. This was partially the result of the fact that more and more people began to live in cities, where they could pose a direct threat to the elites. And after the industrialization of agriculture and of transport had made sure that urban populations could be fed, increasing numbers of people could move to the cities. As a result, the first huge (and rather complex) metropolitan areas emerged, housing many millions of people.

The spread of industry based on fossil fuels all around the world has led to unprecedented levels of the global social division of labour, and thus to a growing global complexity at the expense of local and regional forms of complexity. While the first industrialized nations have succeeded in remaining rather powerful, newcomers are increasingly challenging their positions. Especially since the 1960s, many energy- and labour-intensive industries have moved to areas where the production costs are lower.

Most notably during the twentieth century, people began to create an ever expanding set of microclimates. Not only houses for people were heated during the cold seasons, but also houses for cultivating plants (greenhouses). The next step was to create cold microclimates during the hot seasons. This included refrigerators, specialized railroad cars, freight trucks and ships, which made possible the production and transportation of meat and other perishable foodstuffs on a large scale. Cooled or heated microclimates for comfort and pleasure were the next step. They include climate controlled houses and cars; artificial ice skating rinks and skiing slopes; tropical swimming pools (not very surprising, since we are still a tropical animal). The exploration of space and of the deep seas led to the development of microclimates in the form of space ships and suits, submarines and diving suits. Never before during the history of the Earth has a species created such a diversity of artificial microclimates.

Industrialization has made possible to feed entire populations with unprecedented amounts and varieties of foodstuffs. Especially in societies where the service sector has become dominant, most people perform less manual labour than ever before. As a result, on average they are becoming heavier than ever before in human history. It is not yet clear what the upper limits of the digestible matter and energy flows are, but in affluent societies at least some people appear to be making determined attempts to reach them. In other places, by contrast, great numbers of people still struggle with the opposite problem.

Industrialized societies have become more powerful yet also more vulnerable. Right now, all industrial societies are very dependent on the dwindling stocks of fossil energy. Seen from a long-term perspective, the exploitation of the limited supply of fossil fuels can only be temporary. But, whatever the future may bring, up until today the large scale use of fossil fuels has made possible levels of global cultural complexity that were hitherto unimaginable, although at the cost of the decline of older forms of local and regional complexity. Today, people, matter, energy and information circle the globe in way unprecedented during any period of the Earth's history.

All the matter and energy flows harnessed by humans have resulted in increasing material entropy on the surface of the Earth in the forms of waste products. Even allowing for a possible enhanced greenhouse effect, the generated heat can still be comparatively easily radiated out into the cosmic entropy trash can. But virtually all the material results of human action will remain on this planet. For most of its history, humans have relied on the existing biological waste disposal regime in order to get rid of their trash. Especially since the Industrial Revolution, however, more and more materials have been made that cannot not be easily recycled by terrestrial biology. In addition, more matter has been dispersed across the face of the Earth than ever before. One may wonder whether humans will be able to invent an efficient trash recycling regime and, if not, what the consequences will be.

In the 1940s, scientists in different parts of the world began to explore possible new forms of energy, because they suspected that new and hitherto unimaginably large energy flows could be tapped. The use of nuclear bombs and later the more peaceful uses of nuclear energy demonstrated that they were right. In terms of energy flows, the energy liberated by nuclear fission is part of a rather limited piggy bank of energy on the Earth which originated from supernova events. The energy from hydrogen fusion, by contrast, is stored in a similar piggy bank, but this time originating from the big bang. If people find ways of harnessing the energy flows resulting from nuclear fusion in constructive ways, there may be a great deal of energy available in the future. For the time being, however, most of the energy liberated by both nuclear fission and fusion has been used destructively.

THE INCREASE IN ENERGY USED BY HUMANS

If the numbers presented earlier are correct, there has been a rise in *free energy rate density* from the 20,000 erg/s/g handled by early humans to about 500,000 erg/s/g for contemporary human society as a whole (Chaisson 1991: 139). If true, the *free energy rate densities* during human history would have multiplied by about sixty times. Yet the total energy flow handled by humans has risen considerably more, since the human population as a whole has risen from a few thousands to over six billion today. This represents an increase by a factor of one million. All the energy flows harvested by humans during their history combined must, therefore, have increased by a factor of about sixty million.

Although a reliable breakdown of these energy flows is difficult to achieve right now, a good portion of it is the result of the harvesting of domesticated plants and animals, while most of the rest can be attributed to the exploitation of fossil fuels and nuclear energy. In both cases, we may be reaching the upper limits of the available energy flows that can profitably be exploited. Moreover, it is not clear whether these limits will be sustainable in the long run.

CONCLUSIONS

To sum up, the history of complexity in the Universe consists of a rather boring beginning, followed by a more exciting period of increasing local and regional complexity, which will subsequently peter out into total boredom. This is directly linked to the fact that, from the very beginning, big history has exhibited a trend towards lower energy levels as well as towards energy flows which first increased and then mostly began to decrease. As a result, in most places the level of complexity has remained rather low. This is first of all due to the fact that most of the Universe is virtually empty. Wherever there was sufficient matter, complexity rose in the form of galaxies, which are made up of stars, planets, and clouds of gas and dust, possibly with black holes in their centres. The formation of a growing range of chemical elements needed for life were cooked by exploding stars. This signalled another rise in complexity.

In the beginning, the energy levels determined the level of complexity the Universe could attain. After about 300,000 years of expansion, the rise of complexity has come as a result of the interplay between energy levels and energy flows. The first level of material complexity would be reached as a result of the nuclear force. This complexity consisted of the smallest, subatomic and atomic particles. Electromagnetism would take care of the second, intermediate, stage, in which atoms, molecules and complexes of molecules would be formed. The effects of gravity would inaugurate the last stage and would bring about all the larger structures we know in the observable Universe.

Higher forms of biological and cultural complexity are probably exceedingly rare in the Universe. During the past four billion years or so, the energy flows and levels on the surface of our home planet have been suitable for the emergence of this type of complexity. The intricate energy flows on the Earth's surface first made possible forms of biological complexity. Life began to actively harness more and increasingly varied sources of matter and energy. A very similar process took place during the cultural evolution of humankind. This has led to the highest levels of complexity known today.

There have been specific bandwidths of energy levels and flows which have conditioned the rise and demise of specific types of complexity. The formation of chemical elements, for instance, requires rather high temperatures and pressures, but perhaps not very elevated energy flows. Life, by contrast, requires rather moderate energy levels but rather high energy flows.

Table 1

Energy levels and flows

	Energy levels (temperature, in K or ^{o}C)	**Energy levels (pressure, in atmospheres)**	**Free Energy Rate Desity (Φm in erg/g/s)**
Our Galaxy	Almost 0 K (interstellar space) up to $3x10^9$ K (supernovae)	Almost 0 atm. (interstellar space) up to ?? (supernovae)	0.5
Sun	$15x10^6$ K (core) up to 6000 K (surface)	$340x10^9$ atm. (core) to almost 0 atm. (edge of outer space)	2
Earth	150 K (upper atmosphere) up to 7000 K (core)	Almost 0 atm. (upper atmosphere) up to $5x10^6$ atm. (core)	75
Life	0 ^{o}C up to 90 ^{o}C	1070 atm. (Marianas trench) up to 0.6 atm. (high mountains – air)	900 (plants)
			20,000 (animals)
			150,000 (human brains)
Humanity	20 ^{o}C up to 30 ^{o}C (African savanna)	0.9 atm. (African savanna)	20,000 (proto-humans)
	–20 ^{o}C up to +50 ^{o}C	1 atm. down to 0.6 atm. (high mountains)	50,000 (advanced gatherer-hunters)
			160,000 (early agriculturists)
			260,000 (advanced agriculturists)
		1 atm. down to 0.8 atm. (mountains)	770,000 (industrial society)
			2,300,000 (technological society c.1970)
		1 atm. down to 0.6 atm. (high mountains)	500,000 (all humankind, on average)

Note: This table summarizes the data mentioned before. Please note that sweet water resources, although extremely important for human survival, are not mentioned here.

In order to achieve a more precise picture of the matter and energy flows as well as the energy levels during big history, it will be essential to further quantify them. I am planning to do this in the form of a research program. I therefore invite all interested readers to participate in this exciting adventure.

The growing complexity of living species has exacted a price in the form of shorter life spans. This raises the question of whether we ourselves will become so complex as to drive ourselves to extinction. But whether we will survive or not, today, under pressure from the increasing energy flows tapped by humans, many other living organisms find it increasingly harder to harness sufficient energy in order to survive and, if possible, reproduce. For how long the current processes will last, we do not know. It will depend directly on the ways humans will handle the available matter and energy flows, both in a biological and cultural sense, while preserving complexity on the Earth to the extent that it will provide sufficient room for us to survive and, if possible, reproduce.

NOTES

[1] I am most grateful to Mart Bax, Eric Chaisson, David Christian, Karel van Dam, André Gunder Frank, Gina Giandomenico, Teije de Jong, Gijs Kalsbeek, Arnold Labrie, Koen Martens, William H. McNeill, John R. McNeill, Akop Nazaretyan, Maarten Pieterson, Lucas Reijnders, Graeme Snooks, Jan Spier, Egbert Tellegen, John de Vos, Peter Westbroek, and Antonio Vélez for their insightful commentaries. Of course, they cannot be held responsible for my use of their critique.

[2] The views presented here came as a result of my academic career. I was first trained as a biochemist specializing in genetic engineering of plants. Subsequently, I was trained as a cultural anthropologist and social historian, specializing in religion and politics in Peru. Next came my ten-year experience with organizing a big history course at the University of Amsterdam, which presents a comprehensive view of the past from the origin of the Universe up until life on Earth today. The Amsterdam course was set up following David Christian's pioneering initiative at Macquarie University, Sydney, Australia, in the 1980s. All the scholars teaching in the Amsterdam course have contributed to my better understanding of our all-embracing past. The breakthrough towards my current scheme took place in February of 2003 while the annual Amsterdam big history course was running. Returning from a lecture, my wife Gina – while preparing dinner – asked me why big history happened the way it did. Trying to be as clear and succinct as possible, I suddenly realized that this was a question no one had ever posed to me in such a way. I also saw in a flash that the answer might be both simple and elegant. This essay is my answer to Gina's question.

[3] Leslie White's insights into the workings of energy, entropy and culture within the framework of big history (1943, 1959, 1975) preceded the work of all big historians I know. J. R. McNeill's postscript: *Big Pictures and Long Prospects* in J. R. McNeill and William H. McNeill's recent book: *The Human Web: A Bird's Eye View of World History* (2003: 319–323) are a restatement of Leslie White's agenda combined with Eric Chaisson's general views. After I had formulated my approach, I became aware of Graeme Snooks' theories (beginning in 1996 and most recently expressed in this journal in 2002). Although I find some of his formulations not entirely convincing (especially I do not think that maximizing matter and energy flows has been the dominant strategy), I do think we are on similar tracks.

[4] Although I greatly admire Eric Chaisson's approach, I see some problems with his term *free energy rate density*. I keep wondering whether in addition to mass, volume should also be included in this term. Surely, a star like our Sun is far denser than our galaxy as a whole, or the terrestrial atmosphere, or human society. Clearly, humans would be unable to function if they were packed very close together – they need some space. In Chaisson's approach, these differences are ignored. For future research, I would prefer to define a slightly different term which I will tentatively call *adapted free energy rate density* in terms of energy per time per mass per volume. This correction for volume would lead to more realistic comparisons of the energy flows through matter.

[5] Tainter's book *The Collapse of Complex Societies* (1988) offers a remarkably prescient exception. In this book, Tainter discusses the collapse of complex societies in terms of energy flows.

[6] Cook provided his data in kcal/day/capita. In order to compare them with the data provided by Eric Chaisson in erg/s/g, a conversion factor was needed. Assuming for the sake of simplicity that average body weight throughout human history has been about 40 kilograms (adults and children combined), I calculated that Cook's data needed to be multiplied by a factor of approximately 10^4 in order to convert them to erg/s/g. This leads to the number of 20,000 erg/s/g for early humans, which corresponds surprisingly well to Eric Chaisson's (average) *free energy rate density* for animals (20,000 erg/s/g).

[7] For recent overviews, see Mears 2001, Christian 2004a.

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