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Complexity in Big History

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Introduction

My field of study deals with the very long-range approach to all of history, from the beginning of the universe until life on Earth today, increasingly known as big history. This term was coined by one of its modern pioneers, the historian David Christian, who is also a contributor to this book.

Big history can also be summarized as providing an overview of the rise and demise of complexity in all its forms and manifestations ever since the beginning of the universe. If we want to pursue this approach to big history, we need a theoretical framework that facilitates us to do so. Over the past 15 years I have been reflecting on how to develop such a general theory of big history. In 2001, I found great inspiration in the ground-breaking book Cosmic Evolution: the Rise of Complexity in Nature by US astrophysicist Eric Chaisson [9]. However, I kept a nagging feeling that something was lacking. In 2003, after my wife Gina asked me: "How do you explain all of this," I saw in a flash what was needed to supplement Chaisson's approach and achieve a new synthesis. In my article How Big History Works of 2005 [35], the first contours of this theory were sketched. My book Big History and the Future of Humanity published in 2010 [36] presents a more detailed and improved version of this argument. In this chapter, its key aspects are summarized.

In addition to complexity, my theoretical scheme is based on two familiar physical terms, namely matter and energy. All forms of complexity in big history have consisted of matter, while they have all required an energy flow for their emergence. Our solar system, for instance, is thought to have emerged as a result of the energy flow that was released by an exploding star, a supernova, which had reached the end of its stellar life. This cosmic blast would have compressed a large dust cloud, which subsequently contracted under the influence of gravity to form our solar system. Also the emergence of life must

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have required an energy source of some sort, perhaps the energy released by undersea volcanoes, while all the forms of complexity that humans have produced could not have been made either without energy flows.

After complexity has emerged, it all depends what happens next. Some forms of complexity, such as rocks swinging through space and the general shapes of solar systems and galaxies, do not need any further energy to stay the way they are. Other forms of complexity, by contrast, do need energy to maintain their shapes. If humans, for instance, did not harvest matter and energy from their environment on a regular basis, we would lose our complexity very quickly. And if stars did not release sufficient amounts of energy in their cores, they would collapse under the influence of gravity into neutron stars if they are little, or black holes if they are large.

During their lifetime, stars maintain their complexity through a process of self-regulation. This is based on the interplay between the inward-directed force of gravity and the outward-directed radiation pressure resulting from nuclear fusion in its core. Any gravitational contraction produces higher temperatures in the core and thus speeds up the nuclear fusion process. This releases more energy, which makes the star expand. This stellar enlargement, in its turn, cools down the star and thus slows down the nuclear fusion process again. This lowers the star's radiation output, which makes it contract again. As a result of this negative feedback loop, stars are self-regulating steady-state regimes, which maintain their complexity as long as they do not run out of nuclear fuel. Stars begin their lives with a certain amount of nuclear fuel, mostly hydrogen, which is not replenished during their lifetime. As a result, it is fairly straightforward to predict stellar lifetimes as long as these cosmic light bulbs are not disturbed too much by events from elsewhere in the galaxy.

In contrast to our sun, a planet such as Earth has a rather complex surface. This comes mainly as a result of the interplay between plate tectonics, erosion and life. Two major energy flows keep our planetary surface complexity going, namely the energy flow from within released by nuclear fission processes and the energy received from outside in the form of solar radiation. Also Earth can to some extent considered to be a self-regulating steady-state regime, although its mechanism is more complex than that of the sun, not least because its surface complexity depends on two different energy flows.

While stars and lifeless planets may change as a result of outside influences, they cannot adapt to them, because they lack the necessary feedback mechanisms that would allow them to incorporate those changes into their structure. In other words, stars and lifeless planets are unable to learn from their experiences. Since they make up the largest portion of complexity in the known universe, nature mostly consists of these complex but non-adaptive regimes. Only life, which jointly makes up just a very tiny portion of all the complexity in the universe, can be considered complex adaptive regimes.

At this point in my argument a few remarks about academic terminology are in order. In big history, it is very important to employ technical terms that are understood and accepted within both the natural and social sciences. Unfortunately, there are a good many terms that are understood differently in the various branches of science. The word "system" is one of them. This term is suspect in the social sciences because of its static connotation. This came probably as a result of the social systems approach advocated by U.S. sociologist Talcott Parsons, which was dominant in the 1950s and 1960s. At the same time, the term system is perfectly acceptable within the natural sciences where it has a far more dynamic meaning. As a result of this situation, I prefer to employ the shorthand term "regime" instead of "system." With regimes I simply mean "to some extent structured processes." Following this approach, all forms of complexity are regimes of some sort.

All life forms are far from thermodynamic equilibrium. In order to maintain their complexity, they must harvest matter and energy from outside on a continuous basis in order to keep going. At the same time they are able to learn and adapt thanks to a great many feedback loops based on information. These feedback loops allow life to regulate itself, adapt to changing circumstances, and adapt the environment to its own benefit. Life does so either by Darwin and Wallace's process of natural selection over succeeding generations hardwired in the genome, or by cultural change, which depends on software stored in brains and nerve tissues.

The Goldilocks Principle

Now we have reached the point where I can explain what the addition to my emerging theory was that came as a reaction to Gina's question in 2003, namely that all forms of complexity can only emerge and continue to exist within specific boundary conditions. In other words, for complexity to emerge and continue to exist, the situation has to be "just right." If a situation changes beyond the Goldilocks requirements for that particular type of complexity, it will decline or even fall apart completely. Not very originally, I call this the Goldilocks Principle.

For those readers who are not familiar with the story of Goldilocks: she is a little girl who happened to wander into a house in a forest where three bears live, papa bear, mama bear and baby bear. The bears are, however, not at home. Goldilocks, hungry and adventurous as she is, first tries out the porridge bowls on the counter top. She finds that the porridge in largest bowl is too hot; the middle sized bowl is too cold, but the little bowl is just right. She then tries out the chairs: the largest one is too hard; the middle-sized chair is too soft; and the little one is just right. And so it goes on until the bears come home and do not like what they see. As a result, Goldilocks has to flee.

I am not the first to employ the term Goldilocks principle. Over the past ten years increasing numbers of scientists have begun using this term for indicating the circumstances that are required for the emergence and continued existence of complexity. For natural scientists, the Goldilocks principle may, in fact, be totally obvious, because they perform all their analyses from this point of view, at least implicitly. Surprisingly, however, no one appears to have elaborated the Goldilocks principle systematically for all of big history. My systematic analysis of changing Goldilocks circumstances in combination with the energy flows through matter approach, both leading to the rise and demise of all forms of complexity, from the largest galaxy clusters to the tiniest particles, is what I see as my major theoretical contribution to the understanding of both big history and complexity theory.

Goldilocks requirements never exist only by themselves. They always depend on the type of complexity under consideration. Humans, for instance, cannot live below or above certain temperatures, while our direct needs also include sufficient air pressure, enough oxygen, food and a regular water supply. The Goldilocks requirements for stars, by contrast, are very different. Stars need enormous amounts of closely packed hydrogen in their cores, while they must be surrounded by cold empty space. If that were not the case, they would suffocate in their own heat and blow up as a result. Under the action of gravity stars create so much pressure in their interiors that nuclear fusion processes ignite, converting hydrogen into heavier (and thus more complex) helium nuclei while releasing energy in the form of radiation. These stellar Goldilocks circumstances are very hard to reproduce on Earth, which explains why nuclear fusion has not yet become feasible as a way of generating electricity.

While animals, plants, and even microorganisms have created a great many Goldilocks circumstances that have helped them to survive the vagaries of planetary life, humans can be considered the Goldilocks champions of this planet. Human-created Goldilocks circumstances can have both a social and a material character. Material Goldilocks circumstances include clothing, housing, cars etc., while an example of social Goldilocks circumstances is presented by traffic rules. These rules are meant to define human behavior in ways that allow members of our species to reach their destination relatively efficiently while seeking to preserve the complexity of all the participants involved. Those who fail to obey the traffic rules usually do so in order to reach their destination more quickly at the risk of compromising safety. Similarly, all other social rules can be seen as social Goldilocks circumstances created by humans that are aimed at preserving certain forms of complexity.

Can we define levels of complexity?

While analyzing the rise and demise of complexity in big history, a major unresolved issue is the question of how to unambiguously define all these different levels of complexity. It may well be that a good definition of complexity exists, yet I am not aware of it. Here, I present my temporary solution to this problem, which may not be original at all. My approach of defining different levels of complexity is based on a few, rather obvious, criteria which include the following. First of all, there is the number of available building blocks. Clearly, with more building blocks more complicated structures can be built. For instance, a very large number of hydrogen atoms may jointly form a star. In the second place, the level of complexity can rise when the variety of the building blocks increases. In the third and fourth place, the levels of complexity can go up when the connections and other interactions between and among the building blocks become both more numerous and more varied.

There is another important aspect to complexity, namely sequence. Digital computer information, for instance, consists of only two elementary building blocks, namely ones and zeros. Yet by using enormous amounts of ones and zeros in specific sequences in the form of information humans have been able to generate a great deal of complexity, namely digital computers, including everything that can be done with these amazing machines that are connected to each other in ever larger networks. Apparently, the sequence in which these building blocks are organized can produce considerable levels of complexity, while only a slight change in sequence can wreck this complexity entirely. The sequence of building blocks, and thus information, only plays a role in complex adaptive regimes. In life, the genetic information is usually organized in long strands of DNA molecules, in which the sequence of its four major building blocks, namely adenine, thymine, cytosine and guanine, is of overriding importance for determining what happens inside cells. This DNA structure makes possible feedback loops that turn life into a complex adaptive regime. In a similar way, sequence is also very important for all forms of cultural information and communication.

One may argue that lifeless nature exhibits certain sequences and can thus carries information. Sediments, for instance, may contain layers containing fossils of many different kinds, which are interpreted by scientists as clues to a more or less distant past. Yet there is an important difference between this type of sequence and genetic and cultural information. Whereas sediments do not perform any function for the regime as a whole – they are just there –, the information stored in genetic molecules and cultural depots such as brains, books and hard drives can always be interpreted as having some function for the individuals or societies they form part of.

By defining complexity in terms of building blocks, connections and sequences, it should in principle be possible to determine to what extent the whole is greater than the sum of its parts. Yet in practice this remains very difficult. One wonders which equations would be used, and how the different aspects would be rated. For instance: what would count for more: a greater variety of building blocks, more and more varied connections, or perhaps a longer and more varied sequence? Right now, I find it impossible to rate all these aspects in a way that would allow us to reliably compute all the different levels of complexity. If possible at all, achieving such a goal even in terms of a first order approach could well constitute an entire research agenda. And even if we could achieve this, would this lead to a sufficiently precise characterization of the emergent properties of that particular level of complexity, which are, in the final analysis, its most important characteristic? As a result of all these uncertainties it seems to me that for the time being we will have to rely on qualitative, rather subjective, statements of how to assess all the different levels of complexity that have existed in big history. This may be unsatisfactory, yet to my knowledge it is the best available approach today.

There is another major issue that complicates such calculations. Building blocks at one particular level of complexity may jointly become the building blocks for the next level of complexity. These more complex building blocks are usually linked by different types of connections than those that exist at a lower level of complexity. This makes it even harder to assign values and numbers to building blocks and their connections, and thus achieve a quantitative measurement of complexity in these terms. Quarks, for instance, are thought to be the building blocks of protons and neutrons which, in their turn, can combine to form the nuclei of chemical elements, which may jointly form stars, planets and black holes. These cosmic objects, in their turn, are the building blocks of galaxies which, on a greater level of complexity, may be the building blocks of galaxy clusters. Chemical elements may also combine to form molecules, which can link up to become polymers. At a greater level of complexity, a variegated collection of molecules may jointly form cells, which may combine to form individuals which, in their turn, may be the building blocks of society. All these different levels of complexity are relatively autonomous with regard to each other. As a result, such a particular level of complexity exhibits emergent properties that cannot be entirely explained from the properties of a lower level of complexity.

Let's now take a crude qualitative look at the various levels of complexity that can be discerned in big history. According to many scholars, there are three major types of complexity: physical inanimate nature, life and culture. In terms of matter, lifeless nature is by far the largest portion of all the complexity known to exist in the universe. The following example may help to grasp the significance of its sheer size. Let us assume for the sake of simplicity that the entire Earth's mass equals that of an average American car, about one thousand kilograms. The combined mass of all planetary life would then amount to no more than seventeen micrograms. This more or less equals the weight of a tiny sliver of paint falling off that car. Seen from this perspective, the total mass of our solar system would be equivalent to that of an average supertanker. Since the mass of our galaxy is not well known – let alone the mass of the entire known universe –, it is hard to extend this comparison any further. But one major conclusion stands out. Even if life were as abundant in our galaxy, or in the universe as a whole, as it is within our solar system, its relative total mass would not amount to more than a sliver of paint on a supertanker.

All this cosmic inanimate matter shows varying degrees of complexity ranging from single atoms to entire galaxies. It organizes itself entirely thanks to the fundamental laws of nature. Whereas the resulting structures can be exquisite, inanimate complexity does not make use of any information for its own sustenance. In other words, there are no information centers determining what the physical lifeless world looks like. It does not make any sense, for instance, to wonder where the blueprint of our solar system would be stored that helps to shape Earth or our solar system, because it does not exist.

The second level of complexity is life. As we just saw, in terms of mass life is a rather marginal phenomenon. Yet the complexity of life is far greater than anything attained by lifeless matter. To maintain these elevated levels of complexity, life organizes itself with the aid of hereditary information, usually stored in DNA molecules. While trying to find out how life works, it does make a great deal of sense to wonder where the information centers are located that help configure it; what this information looks like; how the control mechanisms work that store this information and help to translate it into biological shapes; and what the limitations of these mechanisms are in shaping organisms, given the influences they undergo from the outside world.

The third level of complexity consists of culture: information stored as software in nerve and brain cells or in human records of various kinds, ranging from stone tablets to silicon. The species that has developed this capacity the most is, of course, humankind. In terms of total body mass, our species currently makes up about 0.005 per cent of all planetary biomass. If all life combined were just one single a sliver of paint, all human beings today would jointly amount to no more than a tiny colony of bacteria sitting on that flake. Yet through their combined efforts humans have learned to control a considerable portion of the terrestrial biomass, today perhaps as much as between 25 and 40 per cent. In other words, thanks to their culture this tiny colony of microorganisms residing on a sliver of paint has gained control over a considerable portion of that flake. In order to understand how human societies operate, it is therefore not sufficient to only look at their DNA, their molecular mechanisms and the influences from the outside world. We also need to study the cultural information humans have been using to shape both their own lives and considerable portions of the rest of nature.

In contrast to genes, the building blocks of cultural information cannot be defined unambiguously. It is therefore even more difficult to rigorously define cultural complexity. This is not only caused by the fact that cultural concepts are flexible and apt to change very quickly, but also because they need to be interpreted by people. While within living cells genetic information needs to be interpreted unambiguously by its cellular machinery in order to function properly, in human societies such a lack of ambiguity in interpretation is rare, if it ever occurs. Yet although cultural information may often be ambiguous, it is usually (although certainly not always) sufficiently efficient to allow many animals, including humans, to successfully wage the struggle for life.

Energy and complexity

Can we measure and calculate energy flows through matter during all of history? In his book Cosmic Evolution, Eric Chaisson sought to do so by defining the concept of free energy rate density – indicated with the symbol Φm – as the amount of energy that flows through a certain amount of mass during a certain period of time. For human beings, for instance, it is the amount of energy that we ingest during a certain period of time, let's say twenty-four hours, divided by our body mass. In principle, this approach allows us to calculate Φm values for every form of complexity that has ever existed, ranging from the tiniest particles to galaxy clusters. This makes it possible to systematically compare all forms of complexity.

In his analysis, Chaisson showed that there is a clear correlation between the intuitively defined levels of complexity observed in the known universe and the calculated free energy rate densities. Whereas humans may seem vanishingly small compared to most other aspects of big history, we have generated by far the largest free energy rate densities in the known universe. In the following table, Chaisson summarized some of his findings.

For many people, these results are counter-intuitive. One would expect, for instance, the free energy rate density of the Sun to be much greater than the Φm value of our brains. Yet whereas on a daily basis the Sun emits a far greater amount of energy than the energy used by our brains, the free energy rate density of the brain is much larger because the brain is so very little compared to the Sun. More in general, the Φm values of life are considerably greater than those of lifeless matter. Apparently, these tiny living regimes generate much greater free energy rate densities than their lifeless counterparts.

Table 1. Some Estimated Free Energy Rate Densities.

Generic Structures	Approximate Age (10^9 year)	Average Φm (10^{-4} Watt/kg)
galaxies (Milky Way)	12	0.5
stars (Sun)	10	2
planets (Earth)	5	75
plants (biosphere)	3	900
animals (human body)	10^{-2}	20,000
brains (human cranium)	10^{-3}	150,000
society (modern culture)	0	500,000

Before considering these numbers in some more detail, it is important to mention that many other researchers have tried to calculate the amounts of energy that flow through matter, for instance in many living species. In such cases, the term "power density" is often used. Because this term is considerably less cumbersome than "free energy rate density," it has become my preferred term. Yet even though the concept of power density is widely known, it appears that Chaisson has been the first to make a systematic comparison of these values all across nature.

For a good understanding of the numbers provided in this table, we now need to consider Chaisson's calculations in some more detail [9 p.136-139]. Let's start with the Φm value for galaxies. This is, in fact, the value calculated for our own galaxy, with the assumption that all the dark matter is included in its total mass. Unfortunately, we do not know whether dark matter actually exists, which makes the Φm value for our galaxy less certain. In addition, our galaxy is supposed to harbor a rather heavy "black hole" in its core that would consist of extremely dense matter. This black hole would exhibit very little complexity, if at all. All the energy produced by our galaxy only comes from stars. Since black holes and dark matter do not release any energy, while they may make up a considerable portion of the galaxy's mass, they lower its Φm value, which is therefore smaller than the combined average Φm value for all the stars that make up the galaxy. In fact, Chaisson's value for stars was calculated for our sun, which is an average star.

While the energy flows emitted by stars keep themselves going, they did not create the overall structure of the galaxy: this big swirling cloud of stars with huge arms. The energy flows that once gave rise to the galactic structure are absent in Chaisson's calculations. The reason for this is, or it seems to me, that the structure of the galaxy emerged a long time ago while today, it does not need an energy flow anymore to keep going. However, as soon as galaxies collide, a sudden flow of kinetic energy is released which would reshape them. And also within galaxies, there is constant change, including contracting gas clouds and exploding stars. Also these processes release energy flows which reshape these galaxies to some extent. Seen in the long run, however, these energy flows and their effects are probably minute compared to the output of all the combined stars and, as a result, do not have to be taken into account while computing a first rough estimate of the Φm value of our galaxy.

In conclusion: Chaisson's Φm value for galaxies characterizes a relatively stable steady-state galactic regime and not a regime in rapid formation or decline. This is actually the case for all of Chaisson's Φm values: they all characterize dynamic steady-state regimes. In other words, in Chaisson's table the energy flows needed for the emergence of these regimes do not play a role.

Let's now consider Chaisson's Φm value for planets. In actual fact, this value does not reflect the complexity of any known planet as a whole. It was calculated for only a thin slice of the outer shell of Earth by estimating the amount of solar energy that reaches the terrestrial surface during a certain period of time, while using as the total mass the weight of the atmosphere plus an oceanic layer of 30 meters. According to Chaisson, this is where most of our planet's complexity resides. Since today the heat generated inside Earth reaching the surface is several thousand times smaller than the solar energy received, Chaisson did not include this geothermal energy in his calculation.

The next Φm value in Chaisson's table, the average free energy rate density for plants, is an average value that includes all living matter. The value provided for animals was, in fact, calculated for the energy used by the human body. This Φm value was arrived at by calculating the average food intake per body weight. Yet in reality, as Chaisson pointed out, the power densities of vertebrate animals vary by almost an order of magnitude [9, p.186]. This raises the issue of whether those vertebrate animals that sport the largest free energy rate densities, namely birds, should be considered the most complex. Chaisson thinks so, because birds have to navigate in three dimensions. Chaisson's estimate for human society (modern culture) is based on the current energy use of six billion people with an average body weight of about 50 kg (adults and children). In this case, most of the energy does, of course, not flow through human bodies. If it did, humanity would cease to exist instantaneously

The Φm values for human history provided by Chaisson exhibit some further problems. The Dutch scientist Lucas Reijnders, for instance, has pointed out that the number for early humans does not sufficiently include the use of fire. Especially by burning large tracts of land, the early folk might have manipulated enormous energy flows, with the aid of which they created desired forms of complexity such as grasslands, while destroying other forms of complexity, usually woodlands. This fiery action would have created landscapes that attracted large grazers, which could be hunted. By stoking fires, they roasted food, while keeping themselves warm and safe from predators. In doing so, recent Australian aboriginals would have produced power densities between one and two orders of magnitude larger than those of the average U.S. citizen in 1997, mostly thanks to the fact that the aboriginals engaged in extensive land burning. This makes one wonder how large the power densities were that the early folk were able to achieve in Australia and elsewhere, wherever nature could be set on fire on a large scale. If one uses power density as a measure of complexity, as Chaisson suggests, aboriginal society would have been much more complex than modern industrial societies. This seems unsatisfactory to me.

Today, most of the energy employed by humans is not used for keeping their bodies going or for burning the land but for the creation and destruction of what I call forms of constructed complexity. With this term I indicate all the material complexity that has ever been created by humans. These include clothing, tools, housing, engines and machines, means of communication, etc. With the aid of these things humans have transformed both the surrounding natural environment and themselves. To be sure: not only humans but also many animals have produced a great many forms of complexity. Well-known examples include spider webs and beaver dams. Yet it seems fair to say that humans have developed this capacity to a far greater extent than any other living species.

The complexity constructed by humans can be divided into two major categories. The first category consists of things that do not need an energy flow for their intended functioning such as clothing, houses, etc. As a result of outside effects, all of these things need, of course, some maintenance from time to time for their continued existence, yet they do not need any energy to perform their intended functions. This type of complexity is made by humans as well as by a great many other animals. The second category of constructed complexity consists of things that require continuous energy flow for their intended functioning. I call them forms of powered constructed complexity. This category includes machines driven by wind, water, fossil fuels or electricity. To my knowledge, only humans have constructed forms of complexity that are driven by external energy sources. In this respect, humans are unique in the known universe.

Many forms of powered constructed complexity exhibit much higher power densities than the Φm values of human brains (about 15 Watt/kg) or human societies (about 50 Watt/kg). As Chaisson pointed out, jet engines achieve Φm values between 2000 Watt/kg (Boeing 747) and 80,000 Watt/kg (F-117 Nighthawk) [9, p.201]. Relatively high Φm values are not only characteristic of jet planes but also of a great many household appliances. While performing a few calculations at home, my son Louis and I found that even our humble vacuum cleaner exhibited a Φm value of about 180 Watt/kg, thus outperforming our brains more than tenfold. This does not mean that jet engines and vacuum cleaners should be considered more complex than human brains. Unlike forms of complexity that emerged spontaneously, all forms of constructed complexity are not using this energy for the purpose of achieving greater complexity within themselves. They were designed instead to use these considerable amounts of energy for performing certain tasks, such as moving heavy objects through the air or achieving a certain degree of order within our living space.

Whereas on closer inspection a great many complications emerge, as a first order approach Chaisson's analysis seems fair enough. In doing so, he has created what U.S. physicist Murray Gell-Mann calls "a crude look at the whole," which is considered perfectly legitimate in the natural sciences. In his approach, Chaisson employed these numbers first of all as a way of measuring different levels of complexity. It was his way of tackling the issue of how to rigorously define and measure different levels of complexity. At the same time, Chaisson used these numbers also as an indication of the energy needed to achieve or maintain certain levels of complexity. In what follows here, I will explicitly not employ the concept of free energy rate density as the yardstick for measuring different levels of complexity. It will solely be used as an indication for the energy that is needed for complexity to emerge and continue to exist.

Complexity in Big History

Let's now examine to what extent the proposed approach of energy flows through matter within certain Goldilocks circumstances leading to the rise and demise of complexity indeed helps us to attain a better understanding of these processes. In doing so, we will very quickly traverse all of history. To be sure, within the context of this chapter any summary of big history can by necessity touch upon only a few key events. A more detailed discussion can be found in my book *Big History and the Future of Humanity*.

At the beginning of space and time, the universe would have emerged with a big bang. An infinitely small singularity would have exploded that contained all the still undifferentiated cosmic matter and energy. This big bang produced the expansion of the universe that we can measure today with the aid of redshifted electromagnetic radiation emitted by cosmic objects. Based on these data, it is estimated that the primordial explosion took place around 13.7 billion years ago.

The cosmic expansion led to both a rapid cooling and a decrease of pressure. During a very short period of time this produced Goldilocks circumstances that made possible the emergence of the basic atomic building blocks, namely first protons (hydrogen nuclei) and neutrons, and a little later also electrons and neutrinos. After few minutes, however, while the embryonic universe kept expanding and cooling down, the Goldilocks circumstances that favored this process disappeared and never returned. As a result, these elementary particles only emerged during the very early phase of cosmic history.

Thanks to the continued expansion, favorable circumstances soon emerged that allowed the formation of the nuclei of some heavier chemical elements, most notably helium and deuterium as well as a little lithium. This lasted about 15 minutes. Yet cosmic expansion happened so fast that most matter remained in the form of hydrogen, about 70 percent, while about 27 percent evolved into helium. During this early phase of cosmic evolution, only a few percent of heavier chemical elements emerged. Had the universe expanded much more slowly, almost all matter would have turned into iron, the most stable chemical element. Because very little complexity can be built with the aid of only iron as building blocks, this would have severely limited the emergence of later forms of complexity. Here we see a very powerful demonstration of the importance of Goldilocks circumstances for the history of the universe.

It took about 400,000 years of cosmic expansion until the temperature had decreased to about 3000 K. This provided Goldilocks circumstances for the pairing of the positively and negatively charged particles, which thus canceled out each other's charges. As a result, electromagnetic radiation could suddenly travel through the universe virtually unimpeded, because it was no longer scattered by all these formerly charged particles. This radiation diluted over time as a result of the ongoing cosmic expansion, thus producing the cosmic background radiation that can be observed today all across the sky.

During the period between about five hundred thousand and two billion years after the big bang, Goldilocks circumstances existed that favored the emergence of stars and galaxies out of the primordial matter that had formed earlier, mostly hydrogen and helium. By that time, the universe had cooled down sufficiently, while the matter density was also just right. Up until about five hundred thousand years after the big bang, the universe had been homogeneous to a very high degree. Yet after five hundred thousand years of expansion, under the influence of gravity spontaneously occurring tiny irregularities began to produce large galactic structures. This led to a differentiation between areas with large matter concentrations (galaxies) and areas with very little matter, namely intergalactic space. The unrelenting universal expansion accentuated these differences. Also within galaxies a differentiation took place between areas with large matter concentrations (stars and black holes) and interstellar space.

This separation into areas with and without matter was extremely important for the rest of cosmic history. Had this not happened, no further complexity could have emerged, not least because there would not have been any empty space where entropy could have been dumped in the form of low-level radiation. This type of entropy is an inevitable by-product of the emergence of greater complexity. Eric Chaisson emphasized that had this growing cosmic dumping ground not existed, no greater complexity would have emerged. After about two billion years, no new galaxies were formed in the known universe. Apparently, the circumstances were never Goldilockian anymore for this to happen.

Within stars, new Goldilocks circumstances came into being that favored the emergence of the nuclei of heavier chemical elements, all the way up to iron. This was the result of nuclear fusion processes that ignited as a result of the stars' gravitational contraction. These Goldilocks circumstances in stellar cores are very similar to the conditions that reigned during the early universe. However, there are two major differences. First of all, the early cosmos had been more or less homogenous, while stars and their surroundings are very different indeed. The large matter and energy gradients that had developed between the very dense stars and mostly empty interstellar and intergalactic space allowed stars to get rid of their entropy and keep their complexity going. In the second place, the infant universe changed so very quickly that there was very little time for nuclear fusion to take place. All stars, by contrast, even the shortest shiners, live a great deal longer. As a result, over the course of time stars became the major cosmic furnaces for forging greater complexity at very small scales, thus producing increasing amounts of heavier chemical elements, thanks to the specific Goldilocks circumstances that reign in their cores.

When stars that are at least eight times the size of our sun reach the end of their lives they may detonate. These explosions are called supernovae because they appear to be "large new stars" that suddenly shine very brightly for a short period of time. Indeed, some supernovae produce almost as much light as the entire galaxy they form part of. During these explosions, heavier chemical elements are formed all the way up to uranium. Because these processes last for only very short periods of time, heavy chemical elements are rare. These stellar blasts disperse the heavier chemical elements and thus seed their cosmic surroundings with these new elementary building blocks. As a result, over the course of time galaxies come to contain increasing amounts of more complex chemical elements. When such a galactic dust cloud subsequently contracts to form new stars and planets, the new solar system may contain the building blocks that allow the emergence of forms of greater complexity such as life and culture. It is thought that our solar system emerged from such a galactic dust cloud around 4.6 billion years ago.

Life may have emerged on our planet as early as 3.8 billion years ago. It is not yet certain whether life emerged spontaneously on Earth or whether it emerged elsewhere in the universe and was transported to our home planet later. Whatever the case may have been, both the emergence of life and its continued existence must have required very specific Goldilocks circumstances. For instance, scientists have defined a galactic habitable zone in our Milky Way in which the conditions for life (as we know it) are just right. This zone is defined by its distance from the galactic center. Close to this center, a great many stars exist that end their lives with a bang, which would destroy any life that had formed in their vicinity. Yet these supernovae also forge and spread more complex chemical elements that are needed for life. This means that life could not have emerged very close to its core. But it could not have emerged very close to the edge of the galaxy either, because in such places there were too few supernovae events to accumulate sufficient numbers of heavier chemical elements that are needed for life. As a result, the galactic habitable zone is characterized by sufficient amounts of supernovae that produce the needed heavier chemical elements, while there are not too many star bursts that would flush out life. Calculations show that our galactic habitable zone would have emerged about eight billion years ago as a zone situated between 23,000 and 30,000 light years from the Galactic center (the radius of our galaxy is about 50,000 light years). Since astronomers think that over the course of time fewer supernovae explosions would have taken place while the amounts of heavy chemical elements increased, over the course of time the galactic habitable zone has widened towards both the galactic center and its outer edge.

Within our solar system, a similar habitable zone is thought to exist. This Goldilocks region is first of all defined by the amount of radiation our sun produces. The planets that are too close to the sun, Mercury and Venus, are too hot and are thus unable to support life. Not very surprisingly, our planet Earth finds itself in a Goldilocks position, while Mars may just be outside of the planetary habitable zone, because it is too cold while it does not have any other energy sources that could support life. Yet it is thought possible that on some of the moons of Jupiter and Saturn life may exist, sustained by the energy emanating from within or perhaps even by the tidal forces generated as a result of the fact that these moons orbit large planets.

There are a more Goldilocks circumstances that needed to be met before life could emerge, most notably liquid water, and thus also an atmosphere surrounding a planet that is large enough so that its gravity keeps the water and the atmosphere there for billions of years. Because it is unknown where and how life emerged, scientists are still seeking to define the very specific Goldilocks circumstances within which this would have happened. Yet it is clear that for more than three billion years after life emerged on Earth, our planet has provided Goldilocks circumstances that allowed it to flourish.

Life is powered by sunlight through photosynthesis or by energy emanating from within the Earth released by, for example, undersea volcanoes. This means that all complex adaptive regimes are powered by complex non-adaptive regimes. It may be that life emerged as a result of energy flows from within the Earth generated by the original accretion heat and later by nuclear fission processes. Yet over time, as the energy flows from within decreased in intensity, life became more dependent on solar energy from outside, which over the past 4.6 billion years is thought to have increased about twenty-five percent because of the increasing energy output of the sun.

As James Lovelock has argued with his Gaia hypothesis, it may be that life has created conditions that favor its continued existence. In terms of the process of natural selection or, as some prefer, non-random elimination, this makes perfect sense. Surely, any organism that created and maintained Goldilocks circumstances favoring its continued existence (or at least not hampering its survival) had an easier time surviving than life forms which produced circumstances that threatened their survival. To be sure, Goldilocks circumstances for one species may well be unfavorable circumstances for other species, which might be eliminated as a result. Yet the overall effect of this process would have been a biosphere occupied by species that are not diminishing their own chances for survival to the extent that they drive themselves to extinction (at least in the short term), while some of them may actually be improving their living conditions. This is the regime of Gaia as I understand it. As a result of cosmic influences, changing condition of Earth's surface through plate tectonics, and the dynamics of biological evolution interacting with the biosphere, Gaia keeps changing, thus conditioning the circumstances that make possible the rise and demise of complex adaptive regimes. This led to the history of life as we understand it today.

Let's now make a big leap in biological evolution and consider the rise of human beings. The first early humans may have emerged around six million years ago. These were ape-like creatures living in woodlands that may already have begun to acquire stretched legs. Yet it seems clear that around four million years ago, decisive change took place on the emerging East African savannas. This landscape was (and still is) characterized by a rather mild climate. All year round, temperatures would have ranged between 20 and 30 degrees Celsius. This temperature range did not differ a great deal from the average human body temperature, yet it was low enough to allow the early humans to get rid of heir excess heat. As a result, the early hominids who lived there would not have needed any protection against high or low temperatures such as hairy skins. Also the air pressure on the East African savannas is rather mild, on average about 900 hPa.

Why did these early humans with an upright stride, known as Australopithecines, emerge in this habitat? According to the modern scientific view, they owed their emergence to specific Goldilocks circumstances that were only characteristic of East Africa. During this period for reasons not yet well understood, the African continent was becoming drier and colder. This had profound effects on the African flora and fauna. The tropical forests were receding on both the eastern and western sides of Central Africa and were being replaced by savannas. As a result, all forest-dwelling species found themselves increasingly under pressure to adapt to a new life on the emerging savanna grasslands that were interspersed with trees. Among many larger species, including antelopes, other herbivores and hominids, this led to the innovation of stiffer, stretched, legs. While more elastic legs are better for moving around in forested areas, stiffer legs are superior for living on grasslands, because they allow individuals to run faster and cover longer distances. In other words, stretched legs are more energy efficient in those circumstances. Whereas many species adapted in such ways and underwent adaptive radiations, only among early humans would this have led to clear bipedalism: an upright way of walking. During this period, a whole range of early humans emerged.

This is not the place to elaborate all of human evolution in great detail. In what follows I will only touch on certain aspects of human history. Again, a more detailed account can be found in my book *Big History and the Future of Humanity*. After 2 million years of Australopithecines roaming East and Southern Africa, the much brainier *Homo erectus* evolved about 1.8 million years ago, also in East Africa. This considerably smarter human species subsequently spread over large parts of Eurasian continent, in fact to all areas that could be reached by walking and that were not too cold or otherwise uninhabitable. *Homo erectus* made tools and later began to domesticate fire, both of which helped to control more energy resources and shape their environment, even though their bigger brains guzzled up more energy also. Apparently, this energy trade-off was sufficiently good to ensure their survival. About two hundred thousand years ago, modern *Homo sapiens* evolved, again in Africa, from where it spread across all the continents with the exception of Antarctica (where it was too cold). As part of this process, over the course of time the older human forms went extinct while only *Homo sapiens* remained.

Early humans began to create forms of constructed complexity with the aid of culture. Their increasing use and mutual exchange through language of brain software in the form of learned behavior is what has allowed humans to become what they are now and construct all the complexity and artificial Goldilocks circumstances that they have made throughout human history.

A major distinction between the ways these hominids and other animals constructed complexity was that perhaps as early as 3.5 million years ago, humans began to use tools for creating complexity (or for destroying it). To be sure, animals also use tools, but they never employ them for making things. Furthermore, over the course of time only humans have learned to use external energy sources for producing or powering complexity. Their first major external energy source was probably fire control. This allowed humans to expand the range of constructed complexity far beyond anything other animals had achieved, including cooking, heating and providing light during the night. But perhaps even more importantly, humans began to change the complexity of entire landscapes by setting them on fire. Other external energy sources that were harnessed later included animal power as well as wind and water power. It is only very recently that humans began to use fossil and nuclear fuels.

The agrarian revolution, which took off about 10,000 years ago, can be seen as a process of two types of complex adaptive regimes, namely human beings on the one hand and plants and animals on the other hand, that mutually adapted to each other under human dominance, with the human aim to harvest increasing amounts of matter and energy from the biosphere. This process is still continuing today. As a result, humans now control between twenty-five and forty percent of the energy that flows within the web of life. The first agrarian societies all emerged in subtropical mountainous areas after the last ice age had ended. These were apparently the Goldilocks circumstances that favored the rise of agriculture.

The subsequent process of state formation and development, starting between 6000 and 5000 years ago, can be seen as the institutionalization of inequality among humans. Within the emerging states, increasing numbers of humans derived their matter and energy flows no longer from working the land but from other humans. Ever since that time, these matter and energy exchanges have been based on the power and dependency relations prevailing, which were usually unequal. As a result, there have been no states in human history that were based on a more or less equal exchange of matter and energy anywhere close to what is thought to have been the situation among certain groups of gatherers and hunters in the very recent past which, in their turn, may reflect the life ways of the ancient folk before states emerged.

States could emerge as a result of the fact that by practicing agriculture, humans could in principle produce a surplus. In addition, as humans became tied to the land they worked, this led to population growth. Among agrarian societies, it is profitable to have a considerable number of children, because they are productive at an early age while they hopefully provide your retirement fund. Yet population growth led to a further pressure on the resources, and thus to both migration and more restrictions for those who stayed behind. Furthermore, as Robert Carneiro pointed out, the first states all emerged within very restricted ecological conditions, usually river valleys surrounded by dry areas. All of these were, apparently, the Goldilocks circumstances that were required for early state formation. Within states, humans learned to adapt to each other while living within an often very unequal power structure. These social structures were, of course, never completely uncontested. Also states and their neighbors in whatever form of societal development can be seen as complex adaptive regimes that need to continuously adapt to each other. This ranges from attempts at complete destruction of the neighbors to an almost complete submission to them.

In addition to their own muscle power, humans used energy sources from outside ranging from animal power to wind and water power for constructing complexity for thousands of years. With the onset of the Industrial Revolution, however, steam engines and internal combustion engines driven by fossil fuels allowed humans to expand their constructive and destructive capabilities beyond anything other life forms had achieved. As a result, our species began to adapt nature ever more to its wishes and desires, as long as there was sufficient matter and energy available as well as enough space to get rid of the inevitable entropy. All these human enterprises can be interpreted as efforts to produce Goldilocks circumstances for themselves, while sometimes seeking to destroy the Goldilocks circumstances of others. This has led to unprecedented population growth. Yet right now, we may be approaching the end of the era of cheap fossil fuels, if not their imminent exhaustion. If humans want to keep creating similar amounts of complexity, they will urgently need new energy sources. At this moment, solar energy appears to offer the best option, yet today in many places it is still more expensive than the energy extracted from fossil fuels.

In biological nature as a result of the process of non-random elimination, Gaia has produced a global trash recycling regime that allows life to deal with its entropy problem. Humans are now making some efforts to do so also, yet we still have to find a good solution for this issue. At the same time, both matter (in the form of important natural resources) and energy from fossil fuels will become scarce in the near future. These may be the most important issues humanity faces today. Are we able to adapt ourselves sufficiently to the changing circumstances we have brought about by our collective actions and maintain our complexity with the aid of different matter and energy sources, or will humanity be eliminated by Gaia as a result of a failure to do so?

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