Why are nature´s constants so fine-tuned? The case for an escalating complex universe

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Why is our universe so fine-tuned that life is possible? Is somebody special watching over us[1]?

This question arises if alternative worlds or at least parameter settings of physical laws and forces are considered[2]. In particular, in our universe there is an extreme fine-tuning of the physical constants[3]. It turns out that the overwhelming cases of not so fine-tuned possibilities lead to very unfriendly universes regarding live or our existence[1]. However, our observation point should not hurt the Copernican principle[4] and thus not be a very particular, special point of observation (anthropocentric principle) or a very lucky and rare coincidence. Here we show that the more complex universes (allowing life) in over-compensation cover a major part of all possible states.

Looking at parameter variation of the same set of physical laws the difference in complexity between a universe with and without complex processes such as life is defined. Simple and complex processes or worlds in a multiverse[2] are exactly compared and become comparable by studying their output behaviour. The resulting approach extends the anthropocentric principle. It is a method to compare various processes including dynamic behaviour as well as worlds with different parameter settings. Comparisons include their discrete histories in quantum spin loop theory and basic symmetries.

Simple model calculations verify the argument in clear model examples. We compare different parts of a landscape with different environments (“worlds”). In general (even more so for non-linear functions relating parameter number and their settings to complexity), the most complex environment is taking a major part of the complete space of states accessible for all environments together (Fig. 1). A new state is defined here as an objective different configuration (in principle observable) of the system considered. This implicates that it is sufficient to consider this output behaviour of the system and, hence, the proper (shortest possible) description of its output behaviour.

Re-examination of the anthropocentric principle. In its different variations (strong, weak etc.[5,6]) it considers that in more chaotic worlds the conditions are simply too bad for an observer to exist. The existence of an observer implies a fairly balanced and fine-tuned universe allowing stable atoms, long lasting stars and so on. Even if there are huge numbers of less ordered worlds, there is nobody in them to observe or wonder. According to this anthropocentric principle, we are very lucky or an extremely rare accident, maybe even with almost zero probability[7]. However, our existence would thus hurt the Copernican principle[4] and be a rare or unique point of observation. Note that the anthropocentric principle is a bit *ad hoc* as it depends on the fact that we just happen to be there. Furthermore, it identifies besides general principles for any intelligent existence many specific features necessary for our existence but not necessary for every kind of intelligent observer[6]. In contrast, our argument provides a more concrete explanation and, furthermore, does not hurt the Copernican principle: High system complexity allows not only an intelligent observer to exist; the delicate parameter choices and conditions necessary (see Table 1S, suppl. material) for high level complexity lead to a large space of different states (Fig. 1) and a complex output for this universe compared to less fine-tuned universes without such a favourable parameter choice or condition.

Moreover, it turns out that our world is more fine-tuned then would be necessary for life or an observer to exist[8]: For instance, the cosmological constant would not need to be so fine-balanced. Further, to allow life, the proton should be quite stable (half life of 10^{16} years), but it turns out to be even much more stable (experimental lower limit of half life at 10^{32} years). Another example is the overall neutrality of electric charges: Small deviations would be compatible with life. However, in our universe the deviation is with high probability zero[8]. Such over-tuning can not be explained by the anthropocentric argument. Instead, we argue here that with less fine-tuning the world would be less complex (in particular, less stable and more chaotic, hence with simpler description and output).

Comparison of complexity in different systems. Systems can often be described ("compressed") by shorter programs with equal output behaviour (Kolmogorov complexity[9]). We next show (Table 1, details in box 1S) that the description of stopping probabilities for computer programs (Chaitin complexity[10]) and even more so for DNA species (regarding survival, mutation or even cell cycle states) is non-compressible complex. Furthermore, the description becomes exceedingly long if interactions (environment) are considered for living systems (interacting with a potentially unlimited environment). This long description corresponds to very complex output behaviour and a large space of different observable states. This can now be applied to better classify and understand complex systems (Table 1; details in Box IS):

In particular, life has specific properties that lead to escalating complexity, i.e. allowing interactions on ever higher or more complex levels. However, this implies that this phenomenon will in general only reside in escalating complex universes which, again, take a very large part (the major part) of the total space of different states available for a multiverse if we compare many different parameter settings for the same physical laws. Philosophically our argument implies that life is no accident. It is a necessity, one of the many emergent and self organizing phenomena our escalating complex universe allows. A search for deeper answers in such a world makes sense, as "escalating complex" denotes here also ever higher levels of interactions, or of organizational levels as well as insights (description levels for our universe).

However, to be able to compare sizes of different worlds you would need perfect perception and to be able to ignore fundamental limitations e.g. by quantum or chaos theory.

We can achieve here only a much simpler comparison: Given the same laws of nature (e.g. forces) but we change the parameters between them (e.g. their strengths) which resulting worlds, those allowing complexity or not will have a "larger size"?

According to the Kopenhagen interpretation[5], we can compare the "sizes" of these worlds only by the different observable states or output they produce. The output consists of the different observable states of the world given a specific parameter setting (we can not and should not compare any ever unobservable quantum or hidden states).

Furthermore, the output behaviour allows studying the system evolution over a chosen observation angle or time (e.g. from the 1st to the last output or bit). This accommodates easily more relativistic concepts of observation (choosing different observation angles) or a background free description (Box IIS).

Dynamic stability or energy flow is also implicitly contained in the output, e.g. chaotic behaviour and instability corresponds to a random output; a stable energy flow allowing an organized structure corresponds to repetition of an organized output pattern over the chosen angle of output observation ("time"). Note that non-compressible Chaitin complexity results only if several processes as complex as computer programs do not only exist but are compared (e.g. for their average stopping probability). This comparison is itself more complex then an individual program. A program implies already interpretation (at least processing) of bits. Together this already demands a sizable level of complexity (allowing a computer or even an observer to exist).

In other words, "Basic laws can set the stage, but they fail to predict the theatre piece." In fact, Chaitin complexity and the O(DNA) complexity (Table 1) show that exactly at this level system effects are so important that a reduction to simple laws misses these and fails to describe the system and its behaviour appropriately including complexity hidden in unknown starting conditions (or, for instance one can remark "life is not simple").

Applications to different modern formalisms in physics are numerous: Applying quantum-spin-loop theory and its time free formalism[11] we can calculate and directly compare world sizes and their different parameter settings for the same physical laws by comparing their resulting complex or simple output behaviour ("different physical worlds") and considering the resulting discrete[11] histories. According to this measure, more complex worlds have also much longer discrete histories and, hence, larger spaces of discrete different states (Suppl. Material, Box IIS). In "theories of everything" (TOE) our principle to analyze complexity to correctly describe our world among alternative world scenarios may identify the correct underlying symmetry (Box IIIS). Moreover, our principle can be turned into a useful heuristic to identify the correct parameter setting in the bewildering multitude of possible parameter settings for valid string theories (Box IIIS).

As a further example, the dark energy parameter is interestingly set such that this maximizes the richness of the structure of our universe. Thus according to the ΛCDM (lambda cold dark matter) model this would require Ω (dark energy density) around 0.74 to yield (as we observe) an almost flat universe with a very rich and complex structure.

Our argument is a fundamental one (Fig. 1). There are many alternative more derived explanations, e.g. fine-tuning by super-intelligent beings[1] or that a selection process maximizing black hole production should yield highest reproduction rate for a universe but will lead at the same time to favourable conditions for life[6]. Apart from such more speculative theories Steinhardt and Turok[12] suggest that fine-tuning may result from iterative cycles of expansion and contraction of our universe (cycling requires again, as acknowledged by the authors themselves, extreme tuning to happen at all). However, non-identical iterations present one possibility and a straight forward way to increase complexity in a non-trivial way. In support of the argument of our paper also by this cycling we obtain definitely more different output states then for a universe with similar conditions with no iterations or with identical or rather similar iteration states.

The multiverse concept is often interpreted as "everything goes", all is possible[2,7]. We suggest here instead that the multiverse may have a clear structure. Our argument helps to chart the entropic structure of the multiverse (previous efforts see e.g.[13]), starting from the simple question which of the parameter settings opens the largest sub-space. We give here a first answer in that sense that we claim that parameter settings allowing escalating complexity (including self organization and life) open in fact such large output state spaces that they take a substantial fraction of the total of all states taking all scenarios together.

[Main 1499 words]

Note: This is a discussion paper / preprint (1st version August 2008) on one specific aspect of a more general theory paper (1st version July 2007) also available at OPUS http://www.opus-bayern.de/uni-wuerzburg/frontdoor.php?source_opus=3353.

Supplementary Information is added (Table IS, Box IS - Box IIIS) including a figure summarizing the main result of the paper.

Acknowledgements Land Bavaria

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Table 1. Complexity in different systems and implications

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1. Complexity Measures:

Kolmorgorov complexity[*]

A shorter description of the process is possible; bit length of the most compact program yielding the same output as process i:

K_i = min [bitlength (compact program for process i)]

Chaitin complexity[†]**:**

The shortest possible description is already as long as the total bit content of the process counting all binary decision / switches made in the system; applies e.g. to average stopping probabilities for computer programs of a given length or for similar complex processes.

$C_i = \Sigma$ (all decisions, switches)

O(DNA) complexity[‡]**:**

Process has no shorter description and is tightly connected to environment and/or other processes; Chaitin complexity times all interactions including higher order interactions between such interacting complexes (e.g. protein-protein interactions or mutation events)

$O(DNA) = \Pi(\Pi_{ij} (C_i))$

2. Implications:

- A classification and formalisms for emergent phenomena such as life (details in Box IS)
- Life is an indicator for a complex universe with many emergent phenomena (see Box IS)
- A heuristic to assist in model and parameter selection for world models in theoretical physics (Box IIIS)

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[*] Kolmogorov complexity[9] describes complexity of systems by the shortest program which can reproduce the complexity of the output (i.e. the different states of the system that an observer can observe).

[†] The survival probability of a living DNA species (let alone life as a whole or our universe) is too complex to describe it short ("compress it") applying Kolmogorov complexity. To show this (details in Box 1S) we first follow the proof by Chaitin[10] who showed for stopping probabilities of computer programs non-compressibility (in the sense of Kolmogorov). We can directly apply this reasoning also to DNA and survival probabilities. This means that DNA guided processes such as their survival probabilities can not be compressed, they can not be described by a shorter program producing the same output behaviour.

[‡] Furthermore, DNA and life in general interact with many other components, e.g. other living species. The environment as a whole is potentially unlimited. The complexity for such interacting processes (in particular for living processes) is again much more complex then Chaitin complexity (i.e. non-interacting processes).

Legend to Fig. 1. Comparing worlds with different complexity and parameter settings. We compare here the same set of laws but vary the parameters governing them. **(a)** In the **simple model** shown a "world" denotes a specific set of physical parameter settings (an environment) in the abstract space of all possible sets of settings and their observable output results Ω. A particular complex world w_i has many basic states. An escalating complex world (allowing ever higher level interactions, e.g. between interaction mediators) becomes by this feature quite complex, self organizing and as a consequence it favours life and observers. With high chance any observer is then in a complex universe, may be even in the most complex one ("world 1"): This easily outnumbers all simpler universes in possibilities for different observable states including states compatible with life. In particular, if the space of different states increases exponential or over-exponential with the number of parameters, the most complex worlds take most of the state space.

(b) Data examples: Environments ("worlds") with 1, 2, 3 up to 10 parameters are compared for the resulting space of different states and their complexity. **Linear Model:** State space of 1, 2 …10 states for these different 10 environments ("worlds"). The total space of all states is now Σ space (n) which here is just $\Sigma n = (n^2 + n)/2 = 55$. **Exponential model:** Space of $2^1, 2^2 \dots 2^{10} = 1,2,4 \dots 1024$ of observable different states. For these ten different environments ("worlds"), total space is now Σ Space (n) which here is $\Sigma 2^n = 2^{(n+1)} - 1$. The biggest "world" takes thus the major part of total space of observable different states. **In general**, the complete space $S = \Sigma S_w i$ summarizes over all environments ("worlds") w. Each world w_i has a space of different observation states $S_w i$. Depending on the number p_{ji} of parameters in each of these worlds or environments we have

$$S = \Sigma (f(w_i)\, p_{ji}) .$$

Already for moderate non-linear functions f(w_i) (e.g. exponential) the parameter-rich worlds (or, more moderate, the environments which favour stable conditions and complexity) take major slices of the total space.

(c) Detailed comparison and calculation: We give as an example calculations based on discrete histories in quantum spin-loop theory (Box IIS)

Methods: Mathematical analysis; test calculations where done on a standard PC; formalisms, detailed calculations and complexity comparisons are given in suppl. Material.

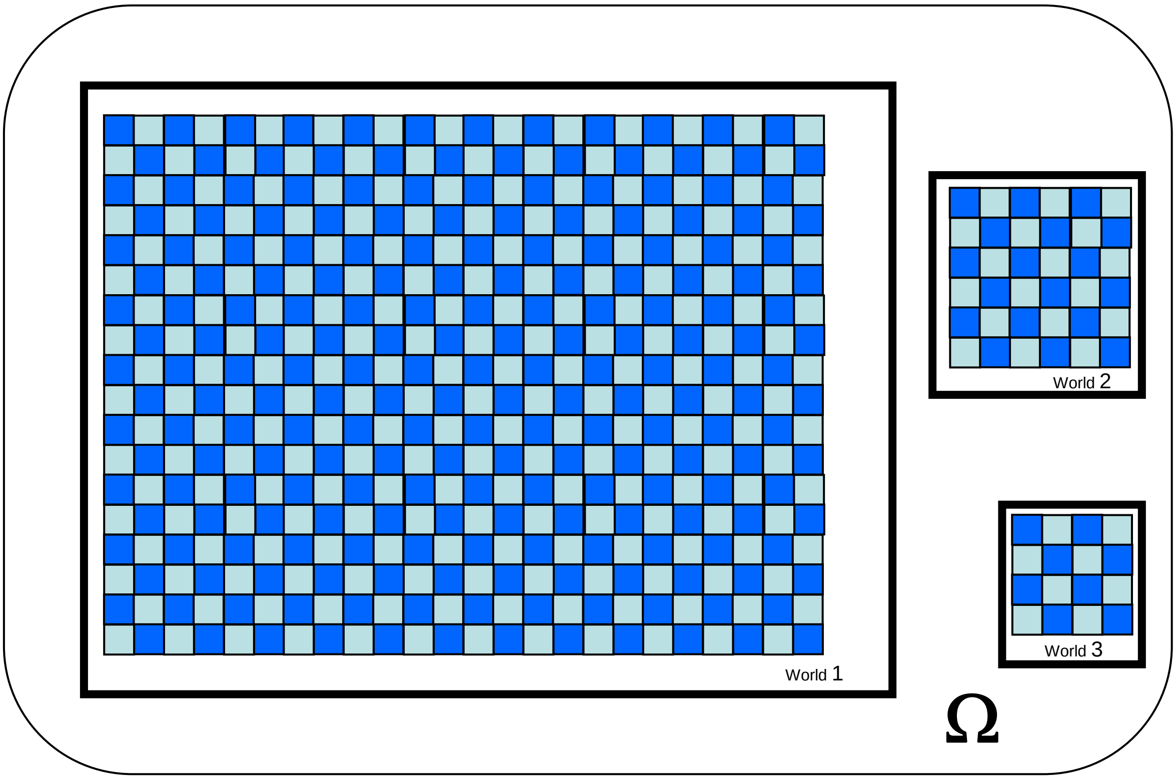

Fig. 1

Supplementary Material (Summary; Table 1S; Box IS, IIS and IIIS)

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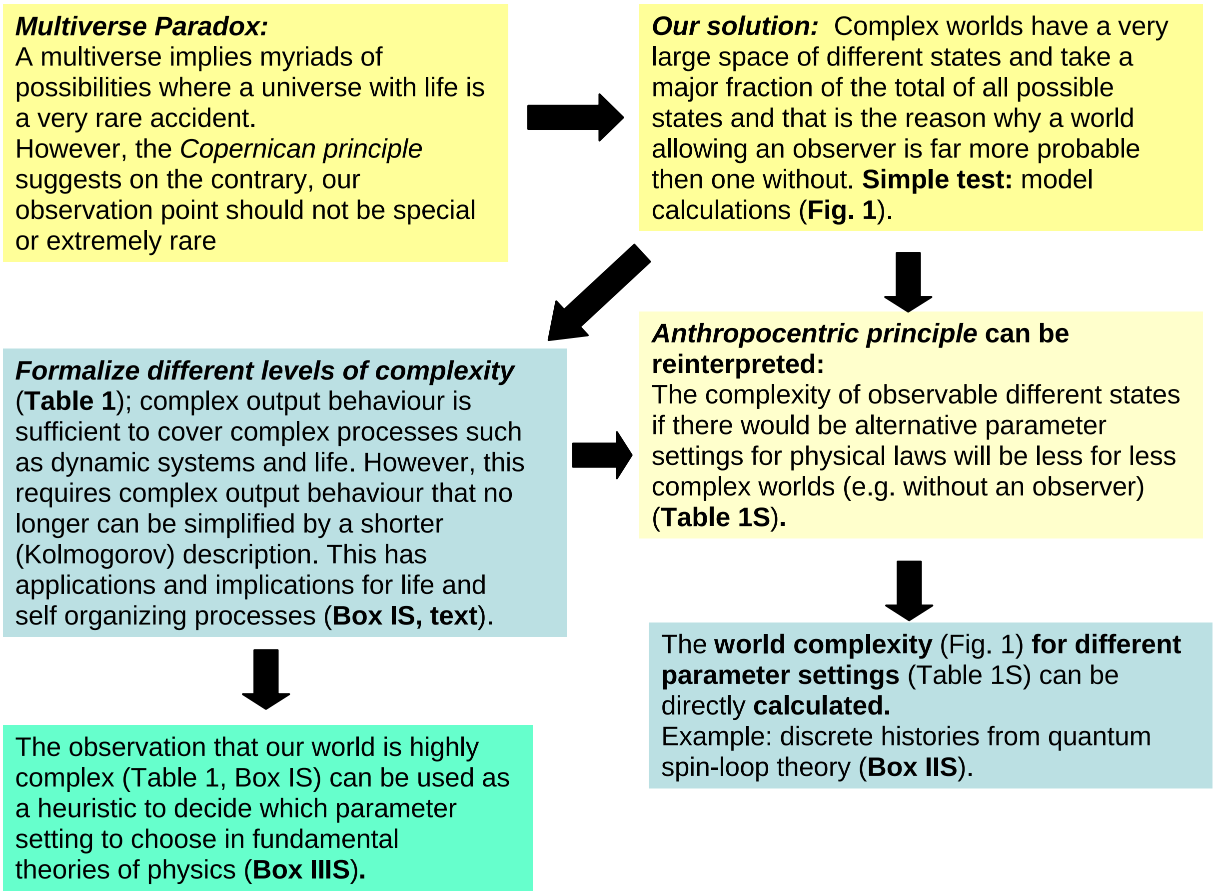
Summary Figure: Flow diagram of the results



Multiverse Paradox:
A multiverse implies myriads of possibilities where a universe with life is a very rare accident.
However, the *Copernican principle* suggests on the contrary, our observation point should not be special or extremely rare

Our solution: Complex worlds have a very large space of different states and take a major fraction of the total of all possible states and that is the reason why a world allowing an observer is far more probable then one without. **Simple test:** model calculations (**Fig. 1**).

Formalize different levels of complexity (**Table 1**); complex output behaviour is sufficient to cover complex processes such as dynamic systems and life. However, this requires complex output behaviour that no longer can be simplified by a shorter (Kolmogorov) description. This has applications and implications for life and self organizing processes (**Box IS, text**).

***Anthropocentric principle* can be reinterpreted:**
The complexity of observable different states if there would be alternative parameter settings for physical laws will be less for less complex worlds (e.g. without an observer) (**Table 1S**).

The observation that our world is highly complex (Table 1, Box IS) can be used as a heuristic to decide which parameter setting to choose in fundamental theories of physics (**Box IIIS).**

The **world complexity** (Fig. 1) **for different parameter settings** (Table 1S) can be directly **calculated.**
Example: discrete histories from quantum spin-loop theory (**Box IIS**).

Table 1S. Examples for the anthropocentric principle and their impact on the complexity of the observed different states

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We analyze here typical examples known for the anthropocentric principle according to INTERS – Interdisciplinary Encyclopedia of Religion and Science[19], edited by G. Tanzella-Nitti, P. Larrey and A. Strumia, (see http://www.inters.org for further details on the anthropocentric principle as well as the works cited therein e.g. from P.A.M. Dirac (The Cosmological Constants, Nature 139 (1937), p. 323), R.H. Dicke (Dirac's Cosmology and Mach's Principle, Nature 192 (1961), pp. 440-441), B. Carter (Large Number Coincidences and the Anthropic Cosmological Principle), B. Carr and M. Rees (The Anthropic Principle and the Structure of the Physical World, Nature" 278 (1979), pp. 605-612), F. Dyson (Disturbing the Universe, Harper & Row, New York - London 1979), J. Barrow (Anthropic Definitions, Quarterly Journal of the Royal Astronomical Society 24 (1983), pp. 146-153) J. Barrow and F. Tipler (The Anthropic Cosmological Principle , Clarendon Press, Oxford 1986) or J. Demaret and D. Lambert (Le principe anthropique. L'homme est-il le centre de l'Univers? Armand Colin, Paris 1994).

The examples concern the fine-tuning of physical constants looking at the four natural constants for the intensity of the interaction of the four fundamental forces, respectively α_g (gravitational), α_e (electromagnetic), α_w(electro-weak nuclear), and α_s(strong nuclear).

Of course it is true that for each of the examples without the respective feature the existence of the observer is not possible (= anthropocentric principle). However, we stress here that the lack of fine-tuning leads often to a collapsed or generally more unstable and much less complex world with a reduced number of observable different states. Such alternative worlds lack specific sources of complexity, such as worlds without atoms, lacking hydrogen or helium or matter at all, or worlds without stars, water or carbon. The number of different observable states is then smaller. Examination of the number of observable states is explanatory for many phenomena of fine-tuning, in particular such that allow better stability or, for instance, additional reactions (see examples). The argument is also directly testable by the examples: Many conditions listed here improve stability for complex states and complexity as well as the richness of different observable states, but have not directly to do with our anthropocentric, specific existence (see also the list of phenomena where there is over-tuning, e.g. regarding the stability of the proton).

Examples:

- α_g the gravitational force, determines the initial rate of expansion of the universe: a higher value then that actually observed leads to a collapse of the whole universe on itself (more or less immediately after its start); however, if the value would be a little bit lower, there would have been no gravitational aggregation of matter, implying no formation of galaxies, stars or planets and low complexity of the resulting universe.

- About 1 sec after the *Big Bang*, neutrinos are decoupled from the rest of the matter, this conserves the ratio between the number of protons and neutrons. The ratio depends very sensitively upon the expansion rate i.e. α_g and on the intensity of the weak interaction α_w regarding the decay of the neutron. However, formation of helium directly from the *Big Bang* depends on the ratio of protons to neutrons and, thus, upon the ratio α_g/α_w. If this ratio is slightly higher, all protons would be transformed into nuclei of helium, there would be no hydrogen and, in consequence, no water. In contrast, a lower value looses the abundance of cosmological helium, with negative impact on the thermodynamic evolution of stars (extremely rapid star evolution, in general much too unstable and short for life to evolve on planets).

- The ratio *a* α_s/α_e is critical for chemistry. The strong nuclear force has to be strong in interactions at a very short range to allow stable atomic nuclei; otherwise there would be no periodic table of chemical elements. If α_e would be a little bit larger, or α_s would be a bit smaller, even the lightest nuclei would not have been stable. Of course also the exact value of the electrical charge *e* has profound implications for the complexity of the resulting chemistry.

- The formation of proto-stellar masses from interstellar gas requires that the contraction reaches a threshold necessary for the nuclear reactions to take place, and this has to happen *before* the same collapse changes the proto-star into an irreversible equilibrium of degenerate gas. If such a threshold of temperature for nuclear reaction to happen could not be reached, the universe would consist only of "failed" stars, there would be no long lasting sun or other stably burning stars. The actual ratio observed allows long and stable main sequence stars for millions or billions of years before they become degenerate stars (e.g. white dwarfs).
- A sufficient number of stars in each galaxy have to explode as a supernova in a complex way to supply heavy elements to interstellar clouds and later planets formed from these. This imposes tight constraints on the values of α_g and of α_w, for instance, the neutrinos produced in the instable supernova phase immediately before the gravitational collapse have to interact sufficiently with the different gas layers of the star, and to push or eject these into outer space.

- *This goes on for every step reaching closer to life*, e.g. carbon is produced in a fine-tuned nuclear reaction from beryllium and helium (Be^8 + He^4 -> C^{12}), whereas production of oxygen (necessary e.g. for water) requires capture of new helium nuclei (C^{12} + He^4 -> O^{16}). The energy level of excited carbon (7,65 Mev) is close to the sum of the energy levels of beryllium and helium (7,37 Mev). Fortunately, carbon synthesis is strongly favoured as the beryllium-helium reaction has a very small cross section. The energy level of oxygen (7,12 Mev) is lower than the sum of the energy levels of the two nuclei that produce it (7,16 Mev). This is lucky as otherwise almost all carbon would yield oxygen in burning stars, there would be nothing left for carbon-based life. Beryllium, not important for life and not allowing a complex chemistry, is lost. Moreover, the formation of crystals and the stability of even more complex macromolecules are linked to critical values of the ratio between the proton and electron masses and of the electrical charge *e*. As a final example, water can be abundantly present at the liquid phase because the average temperature of the biosphere on the surface of the Earth actually falls within the tight interval between its freezing and boiling points (0-100°C). Water has a surprisingly fine-tuned make-up allowing complex biochemistry and emergent phenomena such as life by its features including a very high dielectric constant and heaviest weight at 4°C.

- More general, the inventory of our delicate physical and chemical conditions can easily be further extended. These can then often be interpreted in terms of the anthropocentric principle (e.g. Barrow and Tipler, 1986; Demaret and Lambert, 1994), however, in most cases the fine-tuning allows in particular more complex and self organizing structures and this implies larger state spaces (as measured by their output behaviour). This applies also if radically different parameter settings ("worlds") are considered (e.g. settings without stars or without nucleons).

An interesting further observation is that the universe is "over-tuned"[8]: The parameters are so fine-tuned that not only observers are possible but that the conditions are particular favourable for life (compared to alternative parameters settings). The over-tuning is not expected by the Anthropocentric principle. However, it is to be expected if the observer should reside with high probability in the most, "overwhelmingly" complex universe (even finer tuned parameter settings for stability and complexity allow a particular complex universe, in particular regarding self organisation and emergent phenomena with ever higher levels of complexity).

Box 1S. Comparing measurements for complexity:

Kolmogorov complexity[9] describes complexity of systems by the shortest program which can reproduce this complexity. However, the survival probability of a living DNA species (let alone life as a whole or our universe) is too complex to describe it shortly applying Kolomogorov complexity.

1. Formalism

(i) To show this, we first follow the argument by Chaitin[10]:

He showed that there are an infinite number of mathematical statements which can not be decided by a finite set of axioms. In particular, he investigated O(N), defined as average probabilities for computer programs with a maximum length of N bits to stop. One can show that this number O(N) can not be compressed, i.e. represented by a shorter program. Proof sketch (see also Chaitin, 2006, p. 80): The strategy for demonstrating that O(N) is incompressible is to show that having the first *N* bits of omega would tell me how to solve the Turing halting problem for programs up to length *N* bits. It follows from that conclusion that no program shorter than *N* bits can compute the first *N* bits of O(N). (If such a program existed, I could use it to compute the first *N* bits of O(N) and then use those bits to solve Turing's problem up to *N* bits—a task that is impossible for such a short program.).
Moreover, an infinite set of such numbers { $O(N)_1$, $O(N)_2$, $O(N)_3$, …} even with infinite digits (general case) can be created which all can not be compressed[10].

(ii) We next consider that a DNA string with N bits has similar properties as such numbers of type O(N). We regard the complexity for the probability of a DNA string to stop O(DNA) (regarding dying out, mutation, or its information processing probabilities): Its probability to stop, and the probability that a species dies out in general, can also only be described by a number O(DNA) as complex or even more complex then a number of type

O(N). There are several reasons for this, one is that the halting problem for any DNA based organism replicating with copy number r and probability p(r) is more then Turing complex and NP complete[14]. Furthermore, consider that the probabilities for mutation are in a potentially infinite context (e.g. probabilities of mutation p(m) depend among other things from ionizing radiation which may come from very distant stars or even quasars) and that both mutations and survival are stochastic processes. Both add sufficient to the halting problem regarding a DNA and a species (a population of DNAs, DNA$_{vector\mathbf{i}}$) that its average stopping probabilities (or survival, mutation, information processing probabilities etc.) only can be properly described by non compressible numbers O(N)$_{DNA}$ at least as complex as O(N):

$$O(N)_{DNA}=O(DNA_{vector\mathbf{i}}\ x(r\ x\ p(r))x(1-p(m))x(1-p(\prod_{ii,ij}(\text{selection at all levels}_{ii}\text{ in enviroments}_{ij}))))$$

However, O(N) numbers measure complexity resulting from averages over discrete, closed programs (or processes) which each are independent. In contrast, O(N)$_{DNA}$ numbers consider averages over open processes, interacting with an open (potentially unlimited) environment.

(iii) We cast this into a formalism describing the complexity of an object or even a world. The number of all contained Kolmogorov processes K is compactly described by a program C(K) with length l, and we collect all non-compressible phenomena from the type of O(N) numbers (process averages, stopping probabilities etc.) as well as all more complex interacting non-compressible phenomena such as life (O(DNA) numbers e.g. species, DNAs, other self organizing and selfermergent processes)

$$\text{Complexity (object)} = \text{length } (C(K)) + \{ O(N)_1, O(N)_2, \ \ldots\} + \{ O(DNA)_1, O(DNA)_2, \ldots\}$$

This implies comparing very high up to infinite sets of non-compressible numbers if we want to compare the complexity of objects and in particular the complexity of different worlds (with their variations in their laws of physics). However, this can be done with set theory even for infinite sets and their cardinality. This furthermore shows that our world has no simple description, e.g. in contrast to [15].

2. Consequences: To get such large state spaces, both information storage and processing of this stored information (catalysis) is necessary. Note that "bits" in this sense is non-trivial and only possible in a rather complex universe (difference to simpler definitions for bits who just consider two states for quanta or particles): "Bits" implies here already an observer or a (molecular) program to be properly processed. Furthermore, living processes evolve (including their stored information) to ever higher levels (genetic level: evolution; next higher level: learning, understanding / meaning[16]; next higher level: culture). These properties (catalysis, information storage) are necessary consequences if the parameter set of the physical laws with a maximum size of different observable states is taken. This is also true for self organization with emergent ever higher levels of interactions (potentially unlimited and reaching out to very far distances, e.g. mutations include hits from radiation of very distant stars or quasars) as well as ever new types of interactions (from DNA to neurons, then language, next computer programs, internet and so on). In fact, this can be developed to a complete theory (not shown here) of life and adaptation comparing cellular life in terms of objective different states including general metabolic state space[17], regulatory implications[18] and a new "background free" (as in quantum spin-loop theory[16]) description of evolution.

3. Applications: To exist in an escalating complex universe is sufficient to have phenomena such as life as well as many other phenomena of self organization and ongoing evolution to ever higher levels of complexity. Note that elementary states (nodes) and interactions between them (edges) can quickly become rather complex even with a comparatively limited number of elementary states if the escalating property holds and interactions of interactions (as super-nodes) are iteratively possible. As with recursive functions in general (e.g. Ackermann function) such a space of different states becomes quickly very large. One further level of recursion more leads to an excessive larger space of different states; hence the most complex world probably owns the largest slice of the complete space (Fig. 1).

Self organizing phenomena can be classified and described according to the four levels of complexity given ((i) Kolmogorov; (ii) Chaitin; (iii) DNA-like including interacting processes and (iv) iterative emergent. For instance, DNA-based life can be classified in this way regarding replication (Cell cycle, regulation, number of complexity generating cycles) or regarding growth (including metabolism and its regulation).

Tools to classify and understand complex processes including life can be understood and further developed applying these four classes and measures of complexity. The number of different states is again central. Biological application examples include

(i) analysis and approaches for the calculation of the number of different metabolic states or pathways, for instance applying elementary mode analysis[17].

(ii) The analysis of regulatory networks, in particular the number of stable system states requires negative feed-back loops whereas the number of different system states increases exponentially with the number of positive feedback loops (e.g.[22]). The size of different states correlates also directly with network size, for instance in interactome studies of the proteome, different subnetworks depend on the balance between kinases and phosphatases[23], furthermore different modules shape building blocks of 3- and 4-protein complexes and this modular structure again leads to high adaptability and a high number of system states, for instance in the adhesome[24]. Regarding complexity and emergent phenomena, the coupling of the different processes is critical (see Table 1; differences between Chaitin complexity and O(DNA) complexity or processes). Thus an analysis of how the size of different states increases with tighter coupling can directly be applied in neurobiology to compare different processing units and their processing capabilities as well as their emergent potential (not shown here).

Box IIS. Compare different “world” sizes using quantum spin loop theory

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We apply the spin foam formalism[11] and exactly calculate and compare output behaviour and world sizes for a given set of physical laws but allowing different parameter settings. Elementary quantum states (“microstates”) have transition probabilities to several other states. The model uses for this the quantum spin foam formalism:

$$W(s,s') \sim \Sigma\, \mu(\sigma)\, \Pi\, A_v(\sigma)$$

Here A_v is the vertex amplitude and $\mu(s)$ is a measure term. The sum is over the whole spin foam and the product over all vertices. The spin foam formalism allows to construct a background free physics: Time, space and mass appear as spectra of the quantum spin foam. The formalism allows to compare directly which world is more complex by comparing the size of the spin foam and whether for a given world and its history of observable different state (i.e. its output) there is a shorter description possible. We compare worlds with the same laws the chosen quantum spin loop theory has to obey, but the parameters for forces are varied. This changes the observable behaviour, i.e. “the ouput” of the spin foam and we can derive very general conclusions about the output behaviour of the spin foam: The elementary states of the spin foam are connected with each other, and in general from one state there are transitions to several other states. The spin foam forms a web with many possibilities from each node to continue. However, for a given parameter setting there is only one world (including different macroscopic observer states) and one web, there is no Everett-type[2] splitting of worlds.

We explore now here how in this theory the complexities of different worlds compare, i.e. the complete state space for different spin foams if the parameter settings (given otherwise similar physical laws) are either favourable for a complex environment or not.

Consider a nonrelativistic one-dimensional quantum system with x as its dynamic variable. The propagator W(x,t,x′,t′) then contains the full dynamic information about the system. According to Feynman the propagator can be expressed as a path integral

$$W(x,t,x',t') \sim \int D[x(t)]e^{iS[x]}$$

in which the sum is over the paths x(t) that start at (x′,t′) and end at (x,t) and S[x] is the action of this paths. This basic definition of the quantum formalism can then be used to calculate sums of complex amplitudes $e^{iS[x]}$ over the paths x(t).

In particular, the functional integral is then defined as:

$$\int_{\substack{x(t)=x \\ x(t')=x'}} D[x(t)]e^{iS[x]} \equiv \lim_{N\to\infty} \int dx_1 \ldots dx_{N-1}$$

$$\left\langle x \,|\, e^{-iH_0\frac{(t-t')}{N}} \,|\, x_{N-1} \right\rangle \left\langle x_{N-1} \,|\, e^{-iH_0\frac{(t-t')}{N}} \,|\, x_{N-2} \right\rangle$$

$$\ldots \left\langle x_2 \,|\, e^{-iH_0\frac{(t-t')}{N}} \,|\, x_1 \right\rangle \left\langle x_1 \,|\, e^{-iH_0\frac{(t-t')}{N}} \,|\, x' \right\rangle$$

Similarly, one can of course also use sum-over-paths formalisms for quantum gravity and would then derive path integrals over 4d metrics. However, following Rovelli[16] (pp. 320ff), in the background-free quantum spin loop formalism this corresponds to a *discrete* sum over histories of spin networks. Transition probabilities are between spin networks. The quantity x in the argument of the propagator is not the classical variable but rather a label of an eigenstate of this variable. The transition amplitude is not expressed as an integral over 4d fields but rather as a discrete sum-over-histories s of spin networks. This yields a spin foam:

$$W(s,s') = \sum_{\sigma} A(\sigma)$$

A history is a discrete sequence $\sigma = (s, s_N,\ldots,s_1,s')$ of spin networks. In particular, in this background free scenario, this corresponds to count nodes and ages of the spin foam and compare different sizes of spin foams.

A single history is a product of terms $A(\sigma) = \prod_{\nu} A_{\nu}(\sigma)$. (ν labels the steps of a history).

Now, our claim is that in a more complex universe or better environment (for a “richer” setting of the parameters) the Feynman sum is larger. This is almost trivial to see in this formalism, because then the *discrete* sum over histories is larger in the richer environment (“universe”). More accurately, we can compare the sum n for spin foams of different levels of complexity as defined above:

(i) A Kolmogorov compressible spin foam describes a system with a certain number of states but the “output”, i.e. the observable states (nodes, edges) of the spin foam can be equivalently described by a smaller spin foam

$$A(\sigma) = \prod_{\nu} A_{\nu}(\sigma)$$

with a ν smaller then the ν of the original spin foam.

(ii) A non-compressible spin foam would keep the ν (and thus remain large). It is easy to see that paths using virtual particles and interactions are compressible and do not produce a different observable result from a simpler spin foam. In general it is, however, difficult, to be sure that a spin-foam is non-compressible or in parts non-compressible. The number of different states may of course be simplified for certain discrete histories and the same output (in terms of observable different states) is nevertheless obtained. To be certainly non-compressible (in the sense of Chaitin above) this has to involve stopping probabilities over bit-like processes, which on the macroscopic level allows also much more complex processes such as programs or DNA encoded species with catalytic enzymes and may also involve future computing processes (where then the bits and the program code would be on molecular levels). The Chaitin non-compressibility involves that bits are read or interpreted (requires in this sense an observer) and considers averages over programs (with their discrete histories and output). Only this makes the strong statement possible that such a spin foam can in this aspect certainly not be simplified.

(iii) The number of states n of the system goes rapidly up if this spin foam allows escalating interactions between nodes and edges with higher level nodes, i.e.

$$A(\sigma) = P\{ \prod_{\nu} A_{\nu}(\sigma)\}$$

with P denoting the exponential or over-exponential increase of states by the higher level nodes. If there are such escalating complex interactions possible, the most complex environment has in general the absolute largest proportion of the space of observable states (Fig. 1).

(iv) The **formalism** developed can now be directly **applied to** any example of interest from **Table 1S** including different possibilities for stars (e.g. gravitational pressure stabilized by hydrogen fusion as in our sun; more exotic stars with gravitino annihilation as counter pressure against gravitation which may have occurred in an early phase of our universe but could be far more often in alternative parameter settings etc.) and supports then by different sizes of the discrete histories again our conclusion that our world is particularly rich and complex with very many observable different states compared to alternative parameter settings .

Box IIIS. Applying our argument to unified theories.

Unified theories strive for a unification of all four basic forces. To discuss here all efforts towards the direction of such a "theory of everything" (TOE) is beyond the limits of this article. Instead we will point out here how the principle that an observer tends to reside in a typical observation point (Copernican principle[4]) and, hence, with high probability in a universe with very many different states can also here identify best choices of parameters.

Basic symmetries.

String theory represents all 4 basic forces and particle families by geometric symmetries in a high dimensional space (10 for the five well known string theories or 11 for the unifying M-theory. The additional dimensions are compactified to yield our normal world with time and space (four dimensions) and, to be realistic, with a flat Ricci Metric[20]. However, interestingly, as the five well known string theories are related to each other and again for the reason of the basic symmetry and particle requirements of the basic four forces, these string theories rely on the E_8 group (as does for instance the exceptionally simple TOE by Lisi[21] [which probably is too simple, at least regarding Lie algebras]). The reliance on the E_8 group is most clearly seen in the heterotic string theory. Here the transition from 26 dimensions to 4 dimensions occurs in two steps. First 16 of the original 26 dimensions compactify in a self-consistent way; then 6 of the remaining 10 dimensions. The E_8 symmetry arises in heterotic string theory from the reduction from 26 to 10 dimensions. One needs to endow a 16-dimensional subspace of the orginal 26-dimensional space with an even, unimodular lattice. There are exactly two such lattices in 16 dimensions, one of which is the root lattice of E_8+E_8. Moreover, in Heterotic string theory the first E_8 symmetry can elegantly be used to describe the richness of all our observed particles and interactions of our every day physics (the "four basic forces"), whereas the second E_8 symmetry allows to derive predictions for missing particles and interactions, e.g. regarding dark matter.

The E_8 group is *the exceptional Lie group* E_8. An atlas of Lie groups and representations was achieved recently (http://www.aimath.org/E8/). The magnitude of the E_8 calculation is enormous, 60 gigabytes in size (the human genome is less than a gigabyte in size). The accumulated data on E_8 will need long time of analysis and could have unforeseen implications in mathematics and physics.

However, in complete support of our claim, E_8 is first of all the largest exceptional or in other words the most complex finite root system (as a set of vectors in an 8-dimensional real vector space satisfying certain properties). If an observer exists in a universe, he should with highest probability reside in the universe which has most complexity and that applies for finite root systems to E_8.

Root systems were classified by Wilhelm Killing in the 1890s. He found four infinite classes of Lie algebras, and labelled them A_n, B_n, C_n, and D_n, where n=1,2,3.... He also found five *exceptional* ones: G_2, F_4, E_6, E_7, and E_8. According to our claim, the most complex possibility allows the largest state space of different configurations or states and this is for finite Lie algebras the E_8 symmetrie group. Infinite Lie algebras have many reasons why they are not compatible with our observed physics (in particular, it becomes difficult then to identify particle families or other observable features).

String theory parameter setting. There are many ways to achieve a String theory, in particular theories with 5 scaling variables to comprise the complete class of 7555 quasismooth Calabi-Yau hypersurfaces embedded in weighted 4-space. Furthermore, there are 3,284 theories with more than five variables deining higher-dimensioal manifolds, so called Special Fano Varieties or generalized Calabi-Yau manifolds . The topological holes in the manifold or in other words the string spectra have to fit our observed particles (number, properties, charges) to be realistic. A way to compare such complexities is the counting of instantons. This is an incomplete description of state space as only these are counted, but would give a first estimate. A Mathematica program to calculate this is available from http://www.th.physik.uni-bonn.de/th/People/netah/cy/codes/inst.m

String theory is a very elegant and powerful theoretical framework. Nevertheless, currently there are too many free parameters and in that sense it is currently a “non falsifiable theory “ which is always correct as one of the many possibilities could still fit all observed data. Furthermore, all these possibilities are also difficult to calculate in detail to derive the observed spectrum of particles and often postulate many more particles not [yet] observed. If string theory turns out to be correct (either based on Calabi-Yau manifolds or alternative versions, e.g. based on G2 holonomy manifolds) or becomes part of an even more complete theory our claim would be that the solution with the most complex space of different states is that one which we have also the highest probability to reside in, and hence, most probable will yield the correct string spectrum to fit with our observed particles.

The major implication is that measuring the *complexity and the output state number (output size)* of the different string theory versions is *an objective criterion* to allow a rational and correct choice of the correct string theory instead of an arbitrary choice (or in fact, an undecided plethora of possibilities).

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