Chapter 13
Artificial Cosmogenesis: A New Kind of Cosmology

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Abstract. This paper introduces foundations for a new kind of cosmology. We advocate that computer simulations are needed to address two key cosmological issues. First, the *robustness* of the emergence of complexity, which boils down to ask: "what would remain the same if the tape of the universe were replayed?" Second, the much debated *fine-tuning* issue, which requires to answer the question: "are complex universes rare or common in the space of possible universes?" We argue that computer simulations are indispensable tools to address those two issues scientifically. We first discuss definitions of *possible universes* and of *possible cosmic outcomes*—such as atoms, stars, life or intelligence. This leads us to introduce a generalized Drake-like equation, the *Cosmic Evolution Equation*. It is a modular and conceptual framework to define research agendas in computational cosmology. We outline some studies of alternative complex universes. However, such studies are still in their infancy, and they can be fruitfully developed within a new kind of cosmology, heavily supported by computer simulations,

Artificial Cosmogenesis. The appendix [A] provides argumentative maps of the paper's main thesis.

Keywords: artificial cosmogenesis, cosmic evolution, computational cosmology, digital physics, Drake equation, Cosmic Evolution Equation, robustness, fine-tuning, multiverse.

> *What I cannot create I do not understand*
> On Richard Feynman's blackboard
> at time of death in 1988, as reported in [29]

1 Introduction

I am fond of both computer science and cosmology. However, the methods, concepts and tools used in those two disciplines are very different. Is it possible to

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unite this dual passion? This essay outlines foundations for such a new kind of cosmology, *Artificial Cosmogenesis*.

Broadly speaking, we can distinguish three kinds of science: *deterministic*, *probabilistic* and *computational*. Deterministic science can roughly be characterized by the science Newton practiced. He used physical laws and initial conditions to predict the future and explain the past. The predictions are of an amazing accuracy and the tools used are mathematical equations which are relatively easy to solve. Because of its successes, it is often implicitly considered the typical model of hard science.

However, when there are too many particles in a system, their sheer number and interactions make the newtonian approach weak. In fact, even with only three gravitational bodies the newtonian theory of gravitation fails to make practically useful predictions. The main insight of the founders of statistical physics was to average out the interactions of particles to derive *statistical* laws of behavior, such as the laws of thermodynamics or quantum mechanics.

In recent years, Laurent Nottale generalized this statistical predictability to all scales in nature, by unifying relativity theories with microphysics (see e.g. [41, 42, 43]). This *scale relativity* theory constitutes a revolution in progress in the domain of theoretical physics, since its leads to fundamental theoretical results as well as highly precise and validated predictions (see also [63], p96-97).

But what if our statistical methods also fail or are absent? What if we do not know any way to predict the behavior of a very complex system? An even more general approach is needed. This can be done in a computational view of nature, by theorizing and experimenting with algorithms (see e.g. [71, 70]). The field of Artificial Life constitutes a remarkable application of this view, when it attempts to decipher the most general laws of life, and then to implement and experiment with them in computers. Stephen Wolfram [69] argued at length how important this new kind of science based on computer simulations is. He advocated a wide exploration of simple programs, to study their behavior and properties. He argued that such a new approach is unavoidable if we want to understand complex dynamics. As a matter of fact, the study of complex dynamical systems will in most cases *not* be predictable with simple equations. Wolfram [68, 69] further conjectured that most systems in nature are *computationally irreducible*. This means that to study complex systems, there is no shorter way than to run step by step the model, and study how it behaves (see also [72] for a general formal definition of irreducible computation). Such a kind of science can still make predictions because simulations can be run faster than reality. Studying complex systems, equations won't help, simulations will.

Of course, when possible, it is best to aim for absolute and precise predictions such as in Newtonian science. When this fails, statistical laws are the second best option. But most real and complex systems may not be predictable in these two ways. A broader general computational exploration promises to be the way to understand the rise and evolution of complexity.

My aim in this paper is to propose a computational approach to progress on two arduous cosmological issues. First, the *robustness of the emergence of complexity* in our universe; second, the question of how *fine-tuned* our universe is.

The question of the robustness of the emergence of complexity can simply be illustrated by a thought experiment. *What would remain the same if we would replay the tape of the universe?* To address this issue, we introduce the *Cosmic Evolution Equation* (CEE). It is a modular conceptual framework to discuss possible universes, possible cosmic outcomes, the robustness of the universe and fine-tuning. To define it, we build on Drake's [19] equation in the Search for Extraterrestrial Intelligence (SETI) and on the thoughtful discussion of possible universes by Ellis, Kirchner and Stoeger [23].

The fine-tuning issue is much debated and intricate. The problem is that if we vary one by one a number of parameters, both in cosmological and standard particle models, no life or no complexity of any sort emerges (see e.g. [35, 44, 16]). The issue is mined with logical and probabilistic fallacies (e.g. [39, 14]) as well as physical fallacies (see e.g. [64, 67, 53]). It is also commonly confused with other related issues such as free parameters, parameter sensitivity, metaphysical issues, anthropic principles, observational selection effects, teleology and God's existence [67].

Additionally, different discussions of fine-tuning focus on very different *cosmic outcomes*. We see fine-tuning discussions regarding the dimensionality of space [44], the production of carbon atoms in stars [30], the existence of long-lived stars [1]; the number of black holes [49]; biochemistry [5]; but also complexity of any sort [20]. A key question to clarify the issue is thus to explicitly ask: *fine-tuning for what?* Which cosmic outcome are we interested in? In particular, we will see that most fine-tuning arguments are poor, since they vary parameters one by one, which is a fallacy resulting in exploring only 0,00000000000000456 % of the parameter space under consideration!

To remedy this situation, we generalize the CEE. The Drake equation estimates the number of communicative intelligent civilizations in our galaxy. By extension, one application of the generalized CEE is to estimate the likelihood of our particular universe in the space of possible universes. In other words, if Drake's equation allows to estimate the probability of life existing "somewhere in the galaxy"; one application of the CEE is to estimate the more general probability of life existing "*anywhere* in the space of possible universes". *Artificial Cosmogenesis*—ACosm for short—is the study of alternative cosmic evolutions and allows in principle to assess how fine-tuned our universe is.

We first discuss the issues of possible universes and possible cosmic outcomes (sections 2 and 3). Then we introduce the CEE to discuss the robustness issue (section 4) and generalize the CEE to address the fine-tuning issue (sections 5-6). By bridging the gap between computer science and cosmology, I hope this framework will fruitfully pave the way for resolving these two fundamental cosmological issues.

2 Possible Universes

What are the possible universes? How can we describe the space of possible universes? These questions raise enormous logical, metaphysical, philosophical, and scientific problems. Although possible universes or possible worlds have been discussed centrally in the history of philosophy (see e.g. [2, 36], see also [18] for a wider historical perspective), our aim here is to formulate the issue of possible universes so that it can progressively exit metaphysics and enter the realm of operational science.

We now follow Ellis', Kirchner's and Stoeger's [23] definition of the class of all possible universes. Let M be a structural and dynamical space of all possible universes m. Each universe m is described by a set of states s in a state space S. Each universe m is characterized by a set P of distinguishing parameters p, which are coordinates on S. Such parameters will be logical, physical or dynamical. How will they dynamically evolve? The three authors elaborate:

> Each universe m will evolve from its initial state to some final state according to the dynamics operative, with some or all of its parameters varying as it does so. The course of this evolution of states will be represented by a path in the state space S, depending on the parametrisation of S. Thus, each such path (in degenerate cases a point) is a representation of one of the universes m in M. The coordinates in S will be directly related to the parameters specifying members of M.

In such a procedure, we face a first major issue:

> **Possibility space issue:** *What delimits the set of possibilities? What is the meta-law or meta-cause which determines M?*

As the three authors argue, we can't avoid the meta-law issue, because otherwise we have no basis to set up a consistent description of M. We need to have a logic which describes M. There are other difficult issues related to identifying which different representations represent the same universe models—*the equivalence problem*— and the problem of dealing with an *infinite space of possible universes.* I refer the reader to the three authors' paper for more in depth discussions of these issues.

More directly related to the fine-tuning issue is the remark of Jean-Philippe Uzan that "the larger the possibility space considered, the more fine-tuned the actual universe appears to be" (in [23], p923). Indeed, we can easily increase the unlikelihood of our universe simply by allowing the parameter space to grow. You could ask for example, did you explore if universes with 42 dimensions generate life? Do we really want to capture the radical idea of "all that can happen, happens"? There is much variation in the space of possibility we want to delimit. Ellis ([21], p1261) distinguishes four levels of variation, *weak*, *moderate*, *strong* and *extreme*:

> • "*Weak variation*: e.g. only the values of the constants of physics are allowed to vary? This is an interesting exercise but is certainly not an implementation of the idea 'all that can happen, happens'. It is an extremely constrained set of variations.
> • *Moderate variation*: different symmetry groups, or numbers of dimensions, etc. We might for example consider the possibility landscapes of

> string theory [24] as realistic indications of what may rule multiverses [24, 55, 56]. But that is very far indeed from ‘all that is possible’, for that should certainly include spacetimes not ruled by string theory.
> - *Strong variation*: different numbers and kinds of forces, universes without quantum theory or in which relativity is untrue (e.g. there is an aether), some in which string theory is a good theory for quantum gravity and others where it is not, some with quite different bases for the laws of physics (e.g. no variational principles).
> - *Extreme variation*: universes where physics is not well described by mathematics; with different logic; universes ruled by local deities; allowing magic as in the Harry Potter series of books; with no laws of physics at all? Without even mathematics or logic?”

We indeed need to make a choice between theoretical physics and magic... or anything in between.

Do we need to assume an actual multiverse? No we do not. To study the fine-tuning issue, we need only*possible* or *virtual* universes, not actually realized ones. This interpretation still allows us to use the vast multiverse literature to define and explore possible universes, without making strong and problematic ontological claims regarding their actual existence.

3 Possible Cosmic Outcomes

Once we settle on a framework to define possible universes, a second major issue is to specify the parameters which differentiate possible universes:

> **Cosmic outcomes issue**: *What are the cosmic outcomes? What are the milestones of cosmic evolution? What parameters differentiate possible universes? How do we find those parameters?*

As the three authors mention, the values of the parameters may not be known initially. They may emerge out of *transitions* from one regime to another. For example, sociologists do not explore alternative sociological structures by varying the mass of elementary particles. They start from different, less fundamental parameters, such as the influence of population density, the climate or the media. *The challenge to understand complexity transitions in cosmic evolution is of upmost importance and difficulty.* For example, how did atoms emerge out of the big bang era? How did planets form out of stars and stardust? How did life originate out of molecules? How did consciousness emerge from biological organisms? Etc.

The ideal of reducing such parameters is a major goal of science. The objective is to build a consistent theory and narrative of cosmic evolution, which explains a maximum of cosmic outcomes with a minimum of parameters. Scientific progress is achieved when new theories capture previously free and unexplained parameters (see e.g. [64] for an illustration in physics). We could now extend this attitude to attempt a reduction of other higher parameters (such as life) to fundamental physics and cosmic parameters. However, since we are still very far from such a feat, in our description of possible universes we must assume explicitly higher parameters. Typically, when researchers tackle the issue of the origin of life, they don't start from big bang nucleosynthesis, but they assume the existence of molecules.

Ellis, Kirchner and Stoeger categorize the parameters from the most basic ones to the most complex ones. They distinguish different categories of parameters p_j, with $j = 1$ - 2 describing basic physics; $j = 3$ - 5 describing cosmology and a category of parameters $j = 6$ - 7 related to the emergence of life and higher complexity.

Each category p_j is composed of different parameters i. For example, $p_1(i)$ are basic physics parameters, such that the fine-structure constant; masses, charges and spins of particles, as well as other dimensionless parameters. I refer the reader to the detailed description of the parameters given by the three authors.

However, in each parameter category I would like to add explicitly some random, chance or noise parameters. For example, these could include for $j = 1$ - 5 quantum effects in the early universe; or nonlinear chaotic dynamics which might trigger catastrophic events, such as meteorites impacting planets for $j = 7$. This would certainly complicate the dynamics, but would also make it much more realistic. A dynamical argument can even be advanced that such random events might be essential to the open-ended growth of complexity. An illustration can be found in engineering with the heuristic of *simulated annealing*. It starts by adding important noise into the system, and then gradually reduces it. The purpose of the noise is to shake the system to reach a maximally stable configuration.

Now, how do we decide which cosmic outcomes to keep, and which ones to leave out? At first, we can aim at including a maximum of parameters. Then, we would progressively reduce the number of parameters, as we get better and better insights on how they emerge from more fundamental principles and theories; i.e. from previous parameters. Robert Aunger ([3], p1142-1144) did compile from many authors a list of more than 100 different cosmic outcomes. This is the most comprehensive review I am aware of, ranging from the big bang, the formation of atoms, stars, solar systems, life, DNA, multicellularity, sexual reproduction, fishes, to mammals, agriculture, modern science and space exploration.

However, we can already anticipate a fallacy lurking when considering a large list of cosmic outcomes. Similarly to Uzan's remark for the space of possible universes, we can note that the more cosmic outcomes we have, the more unlikely they will seem. The extreme case is to consider one single object as a cosmic outcome. For example, in intelligent design discussions, they consider a complex object (like a living organism or an airplane) and try to assess the likelihood that it arose by chance. Of course this will be very unlikely! Additionally, as Dawkins [17] argues, natural selection would still constitute a much better candidate explanation than design. A scientist will look for possible mechanisms, theories, which can explain the emergence of complexity. The *a posteriori* probability of a single object isolated from its evolutionary or human context is of weak scientific interest.

To avoid such an error, we need to advance *theoretical reasons* to select certain cosmic outcomes and not others. This is rarely attempted. Most authors propose an arbitrary list without strong theoretical justification. Ellis, Kirchner and Stoeger did not justify their choice of distinguishing parameters; although it is clear that they included a lot of cosmological parameters necessary for their subsequent study of alternative universes with different geometries.

The most promising avenue of research is to focus on thermodynamics (see e.g. [47]). Indeed, all systems need to process energy, which is therefore a universal concept, applicable from the beginning of the universe to our energy hungry technological society. Robert Aunger [3, 4] built on a thermodynamical theory to select cosmic outcomes, *non-equilibrium steady-state transitions*. Each transition involves first an energy innovation, then a structural adjustment and finally a new control mechanism. He thus constructed a consistent selection of cosmic outcomes and evolutionary transitions.

Which cosmic outcomes are contingent and evolutionary? Which ones are necessary and developmental? Are there attractors in the dynamic of cosmic evolutionary development? To answer these issues, we need to explore the *robustness* of the emergence of complexity. Stated otherwise, if we would re-run the tape of the universe, would galaxies, stars, biology and technology arise again and again? The straightforward way to answer those questions, in parallel to a theoretical rationale like Aunger's, is indeed to re-run the tape of the universe. Let us now examine how we can conceptualize and do that.

4 Robustness in Cosmic Evolution

> *what would remain the same if the tape of life were replayed?*
> Stephen Jay Gould [25]
>
> *what would remain the same if the tape of the universe were replayed?*
> Paraphrasing Gould's question to the universe [62]

Answering this latter question, Paul Davies ([15], p317) wrote that if "the universe were re-run a second time, there would be no solar system, no Earth and no people. But the emergence of life and consciousness somewhere and somewhen in the cosmos is, I believe, assured by the underlying laws of nature." Those claims, as Davies acknowledges, are only informed intuitions. How can we test this intuition or different ones scientifically? This is the issue of the *robustness of the emergence of complexity in cosmic evolution.*

A first analysis of the tape metaphor shows its limits. Indeed, if the tape and its player were perfect, we should get exactly the same results when re-running the tape. So, the thought experiment would be trivial. Yet if our universe self-constructs, one question is whether small fluctuations, chance events, noise or random perturbations would lead to slightly different outcomes, or very different ones. This makes the issue of robustness in cosmic evolution highly stimulating.

It is very hard to tackle because it is linked to a great weakness of cosmology as a science: it has only one object of study, our unique universe. More precisely, we can distinguish two fundamental limitations that Ellis ([21], 1216) pointed out:

> **Thesis A1: The universe itself cannot be subjected to physical experimentation**. *We cannot re-run the universe with the same or altered conditions to see what would happen if they were different, so we cannot carry out scientific experiments on the universe itself.* Furthermore,
>
> **Thesis A2: The universe cannot be observationally compared with other universes**. *We cannot compare the universe with any similar object, nor can we test our hypotheses about it by observations determining statistical properties of a known class of physically existing universes.*

Our thesis is that it is possible to address those limitations and the issue of robustness by running computer simulations of our universe. It is important to note that if we replay the tape of *our* universe, we don't aim to actually explore the full space of possible universes. Here, we only aim to assess the robustness of the emergence of the different cosmic outcomes. We thus vary *only* nondeterministic dynamical parameters we discussed above (quantum mechanical effects, random perturbations, nonlinear chaotic dynamics, etc.). An open question is also how we vary the random parameters. How often? How strong is the variation? Various distributions can be tested, from gaussian distributions, where most random variations are of an average strength, few are weak or strong; to power-law distributions, where there are few very strong variations, some medium variations, and most of the time weak random variations.

Because of the inclusion of such parameters, it makes sense to re-run the same universe simulation. By running a multitude of times the simulation, it will be possible to make statistics on the emergence of complexity. An even more straightforward way to make such statistics would be to drastically intensify astrobiology—the search for extraterrestrials. If or when we will find extraterrestrials, we would be able to progressively study the "natural re-runs" of complexity. Additionally, searching for extraterrestrials more complex than us would force us to break with the implicit anthropocentric assumption that life and humans on Earth are the highest development in cosmic evolution. This invites us to speculate on the existence of higher cosmic outcomes, and this opens the way to test our theories of the general evolution of cosmic complexity (see e.g. [10, 65] for modern views on the search for advanced extraterrestrials).

An example of ambitious simulations of *our* universe are the Millennium run simulations [50, 9, 27]. The authors studied the formation, evolution and clustering of galaxies and quasars within the standard (or concordance) model of cosmology. Although they did not run the same simulation in its full complexity many times, the volume space explored is large enough to extract meaningful statistical properties on the evolution of the distribution of matter.

Replaying the tape of our entire universe is still a much more ambitious project, which at present remains unrealistic. We should remain aware that our current models and their associated free parameters are most likely not the ultimate ones. Of course, new theories need to be developed to know what the key parameters of our universe are. In the meantime, a way to progress is to break down the issue into smaller solvable problems. For example, if we want to tackle the robustness up to the emergence of intelligent life, we can write a generalized Drake equation ([23], p925) that we call the *Cosmic Evolution Equation*:

$$N_{life}(m^*) = N_g \cdot N_S \cdot f_S \cdot f_p \cdot n_e \cdot f_l \cdot f_i$$

where $N_{life}(m^*)$ is the number of planets with intelligent life in our particular universe m^*; and

- N_g is the number of galaxies in the model
- N_S is the average number of stars per galaxy
- f_S is the fraction of stars suitable for life
- f_p is the fraction of such stars with planetary systems
- n_e is the mean number of planets which are suitable habitats for life
- f_l is the fraction of planets on which life originates
- f_i is the fraction of life bearing planets with intelligent life.

There are many implicit assumptions in such a framework, for example that life-supporting stars will be Sun-like; or that life starts necessarily on planets and not on more exotic places. We also implicitly assume that the parameters are independent. To deal with dependent parameters, one would need to introduce a bayesian probability framework. Additionally, we may have clear definitions of what stars or galaxies are, but the issues of defining higher cosmic outcomes such as life or intelligence remain of huge scientific debate.

The factors N_g and N_S can nowadays be estimated, while the recent explosion of exoplanets discoveries is allowing us to estimate more and more precisely the factors $f_S \cdot f_p \cdot n_e$. However, huge uncertainties remain regarding the last two factors $f_l \cdot f_i$.

The main interest of such a framework—whether we consider these seven factors to be most relevant or others—is that we can in a first approximation estimate the factors independently. Additionally, *the more we progress in our knowledge of the universe, the larger the distance between factors we can assess.* For example, assessing the number of planets with intelligent life knowing only the number of galaxies seems very hard. But shorter distances between factors are easier to assess. For example, Miller's [40] famous experiment tells us that the probability to have amino acids out of a primordial soup and some energy source is high. Which is indeed an important insight to evaluate $n_e \cdot f_l$.

Let us now imagine that we run multiple times a model of our entire universe m^*. We would be able to interpret the results of the multiple runs of the simulation as a set of *virtual* universes. We would end up with a distribution function $f(m^*)$ combining the probability distributions obtained for each factor.

However, we need to further specify a *possibility space*, which in this case is M^* resulting from the variation of random parameters only; and a measure π^* on M^*. Such a virtual ensemble of simulated universes V would thus be defined as:

$$V = \{M^*, \pi^*, f(m^*)\}$$

The number of planets with intelligent life would then be:

$$N_{life}(m^*) = \int N_g \cdot N_S \cdot f_S \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot \pi^*$$

Note that the integral is necessary to normalize the result according to the measure π^* and distribution function $f(m^*)$.

There are important and subtle issues to make this normalization sound and possible (see again[23]).

Let us give some more concrete possible results such simulation studies would bring. We might conclude that our universe is robust for galaxy-formation, i.e. most simulation runs lead to galaxy formation.

But still, it might turn out that our universe is not robust for intelligent life, i.e. most simulations *do not* lead to the emergence of intelligent life.

We can now take a fresh eye on our question: are cosmic outcomes necessary or contingent? We can define a cosmic outcome as *necessary* if it appears again and again as we re-run the same universe simulation, as *contingent* otherwise. For example, let us take the DNA code in biology: is it necessary that there is a unique DNA code for terrestrial or extraterrestrial biology? In a similar fashion, in economy, is it a necessity in civilizational development that monetary systems converge to a common currency?

We can also compare the cosmic outcome selections. On the one hand we would have the ones resulting from "simulation experiments" (see e.g. [32] for a discussion); and on the other hand the theoretical approaches (such as Aunger's). *Simulation experiments* in cosmology can play the role that *empirical experiments* play in other sciences. This approach can be called "cosmology in silico" or "computational cosmology". In fact, these endeavors are already developing quickly, as illustrated by the Virgo Consortium for Cosmological Supercomputer Simulations.

We have just begun to explore how robust the emergence of complexity in our universe is. If we want to understand it better, we need to perform computer simulations and use existing conceptual, mathematical and statistical tools to design simulation experiments and to assess the results.

However interesting and important this enterprise is, it does not tackle the fine-tuning issue. Indeed, in studying the robustness of our universe, we try to understand the emergence of complexity in *our universe*, whereas to address fine-tuning we must study the place of our particular universe in *the space of possible universes*.

5 Artificial Cosmogenesis or the Study of Alternative Cosmic Evolutions

> *Now, we create a considerable problem. For we are tempted to make statements of comparative reference regarding the properties of our observable Universe with respect to the alternative universes we can imagine possessing different values of their fundamental constants. But there is only one Universe; where do we find the other possible universes against which to compare our own in order to decide how fortunate it is that all these remarkable coincidences that are necessary for our own evolution actually exist?*
>
> Barrow and Tipler ([6], p6)

> *you might end up having a future subject which is "comparative universality"—we have all these laws for the universe that cannot be eliminated as ours and you study them, you talk about them, you compare them, this could be a future subject. Students would be required to pass exams on their ten possible favorite universes ...*
>
> Gregory Chaitin ([1], p339)

This first quote by Barrow and Tipler summarizes the core problem of fine-tuning. The second quote by Chaitin illustrates a core idea towards its resolution. With the robustness issue, we have focused on *our* universe. To assess in how far our universe is fine-tuned, we must study the place of our universe in the *space of possible universes.* We call this space the *virtual multiverse.*

Fine-tuning arguments vary just one parameter, a fallacy which is nearly *always* committed. The underlying assumption is that parameters are independent. As Stenger ([53], p70) remarks, this is "both dubious and scientifically shoddy". If the history of physics learned us something, it is that phenomena which where thought to be widely independent, turned out to have common underlying causes and principles. For example, our common sense fails to see a connection between the fall of an apple and the tides; magnetism and electricity; and even less between space, time and the speed of light. But all these phenomena have been unified thanks to physical theories.

Additionally, varying several parameters without care can lead to what is known as the *one-factor-at-a-time* (OAT) paradox in sensitivity analysis. The problem with the OAT method is that it is non-explorative. Let us see why. At first sight, it seems logical and rigorous, since it varies factors one-at-a-time while keeping the others constant. It seems consistent because the output from a change can be attributed unambiguously to the change of one factor. It also never detects non-influential factors as relevant. However, by construction, this method is non-explorative, with exploration decreasing rapidly with the number of factors. For a simple example, consider Figure 1, which shows clearly that OAT explores only 5 points forming a cross, out of 9 points in total.

Let us now generalize this example with a geometrical interpretation of the parameter space. In n-dimensions, the n-cross will necessarily be inscribed in the n-sphere. The problem is that this n-sphere represents a small percentage

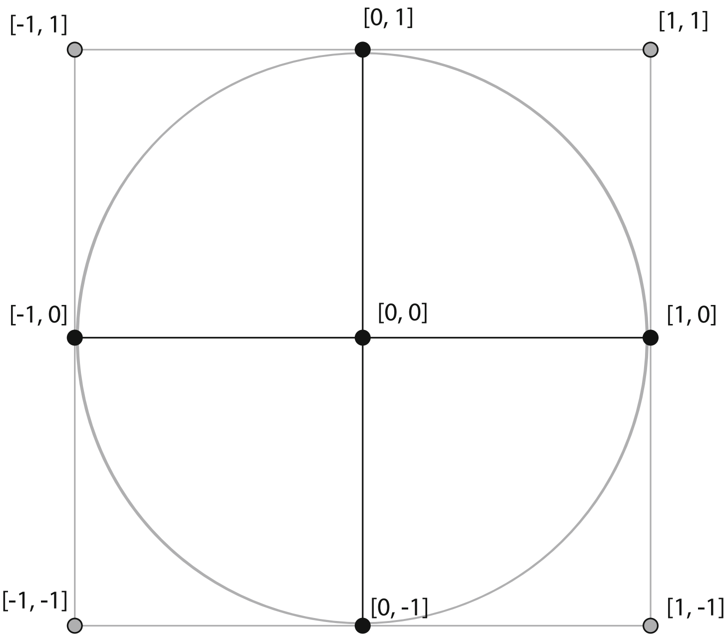

Fig. 1. The one-factor-at-a-time method can only reach points on the cross. In this simple two-dimensional parameter space, each discrete factors can only take values 0, 1 or -1. OAT can reach [0, 0], [0, 1], [0, -1] (points on the vertical line); and [-1, 0], [1, 0] (points on the horizontal line). The points explored are thus on a cross. The points not explored are the corners [-1, 1], [-1, -1], [1, 1], [1, -1]. In a geometrical interpretation, note that the cross is by construction inscribed in the circle. But OAT actually restricts the exploration to points on the cross, not inside the circle because exploring points inside the circle would imply varying two parameters at the same time. Now, that cross itself is inscribed in the circle. In sum, OAT restricts the exploration to the cross, not the circle, but the cross is inscribed in the circle. And this circle is inscribed in the square (2-cube), which is why OAT can't reach the corners of the square.

of the total parameter space defined by the n-cube. This is illustrated in Figure 1, where the cross explored is inscribed in the circle of center [0, 0] and radius 1. In this 2-dimensional example, the ratio of the partially explored to the total area—i.e. the square minus the circle—is $r \approx 0{,}78$. The problem gets quickly worse as we increase the number of dimensions. In 3 dimensions, r $\approx$ 0,52 and in 12 dimensions, r $\approx$ 0,000326 (see [46] for those calculations, as well as critiques and alternatives to OAT).

Fine-tuning arguments typically vary one parameter at a time. So, they use the OAT method to explore the space of alternative universes by varying one by one some of the 31 fundamental physics and cosmic parameters. They actually explore only r $\approx 4,56.10^{-15}$ of the parameter space. We conclude that such fine-tuning arguments have restricted their exploration to 0,00000000000000456 % of the relevant parameter space![1] Can we hope to explore more of this space? How can we proceed?

Let us first call a *fecund universe* a universe generating at least as much complexity as our own. *Are fecund universes rare or common in the multiverse?* This is the core issue of fine-tuning. To answer it demands to explore this virtual multiverse. Milan Ćirković [13] and I both converged on this conclusion. Ćirković used the metaphor of sailing the archipelago of possible universes; I proposed to perform simulations of possible universes, an endeavor called *Artificial Cosmogenesis* (or ACosm, see [62];[64]; and also [60]; [61] for critiques; and [66] for replies). Such simulations would enable us not only to understand our own universe (with "real-world modelling", or processes-as-we-know-them) but also other *possible* universes (with "artificial-world modelling", or processes-as-they-could-be). We thus need to develop methods, concepts and simulation tools to explore the space of possible universes (the "cosmic landscape" as Leonard Susskind [55] calls it in the framework of string theory). In [62], I proposed to call this new field of research *Artificial Cosmogenesis* because it sets forth a "general cosmology", in analogy with Artificial Life (ALife) which appeared with the help of computer simulations to enquiry about a "general biology". However, recent work on the EvoGrid[2] simulation project suggests that the growth of complexity is more likely to remain open-ended if stochastic, non-deterministic processing is used at the bottom, instead of deterministic rules, like in ALife.

Now that we have a framework to define possible universes, we will need to generalize the "Cosmic Evolution Equation" we used to assess the robustness of our universe to explore not only our universe m^*, but also all universes m element of the wider class of possible universes M. This constitutes a rigorous approach to assess how fine-tuned our universe is. However, it is important to understand that the results of such studies would not *ipso facto* provide an *explanation* of fine-tuning. Only if it turns out that our kind of complex universe is common, then an explanation of fine-tuning would be a principle of *fecundity*: "there is no fine-tuning, because intelligent life of some form will emerge under extremely varied circumstances" ([57], p4).

Most fine-tuning arguments change just one parameter at a time and conclude that the resulting universe is not fit for developing complexity. This leads to the "one-factor-at-a-time" paradox. What if we would change *several* parameters at the same time? Systematically exploring the multiple variation of parameters seems like a very cumbersome enterprise. As Gribbin and Rees wrote ([26], p269):

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[1] I used the formulae in ([46], 1510) for this calculation. Note that this assumes that we can put upper and lower boundaries on each of the parameters, which is not at all warranted for physics and cosmic parameters. Note also that this is a very generous estimate, since the actual exploration of OAT will only be a tiny n-cross within the volume of the n-sphere, which itself represents only $4,56.10^{-15}$ of the full parameter space defined by the n-cube.

[2] http://www.evogrid.org

> If we modify the value of one of the fundamental constants, something invariably goes wrong, leading to a universe that is inhospitable to life as we know it. When we adjust a second constant in an attempt to fix the problem(s), the result, generally, is to create three new problems for every one that we "solve". The conditions in our universe really do seem to be uniquely suitable for life forms like ourselves, and perhaps even for any form of organic complexity.

Back in 1991, it indeed seemed very difficult to explore and find alternative universe. However, a way to overcome this problem is to use *computer simulations* to test systematical modifications of parameters' values. In varying just one parameter, parameter sensitivity arguments have only begun to explore possible universes, like a baby wetting his toes for the first time on the seashore. Surely, we had to start somewhere. But it is truly a tiny exploration. Furthermore, maybe there is a deep link between the different constants and physical laws, such that it makes no sense to change just one parameter at a time. Changing a parameter would automatically perturb other parameters (see [11], p1581). Fortunately, more recent research have gone much further than these one-parameter variations.

What happens when we vary multiple parameters? Let us first generalize the Cosmic Evolution Equation, which this time includes other possible cosmic *evolutions*—notice the plural! Let us imagine that we run multiple times simulations of different models of universes m. We interpret the results of the multiple runs of the simulations as a set of *virtual* universes. We end up with a distribution function $f(m)$ combining the probability distributions obtained for each factor of the CEE. Let us mention that, based on modern developments in computer science, there is another more theoretical way to study and choose distribution functions for possible universes (see the remarkable study of Schmidhuber [48]).

The *possibility space* is the huge M resulting from the definition of possible universes; and we add a measure π on M. The resulting ensemble of simulated universes E would thus be defined as:

$$E = \{M, \pi, f(m)\}$$

The number of planets with intelligent life would then be:

$$N_{life}(m) = \int N_g \cdot N_S \cdot f_S \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot \pi$$

We are now talking about cosmic outcomes in other universes. The topic becomes quite speculative, because it is not clear at all *which* cosmic outcomes are the most relevant to assess. The factors in the equation above might be totally irrelevant. What if other possible universes do not generate objects like galaxies, stars and planets, but completely different kinds of complex structures? Nothing *that we know* may evolve anymore... but other things might! We now see the fundamental importance to define cosmic outcomes and the emergence of complexity in a very general manner, so they can also apply to other possible universes. Bradford [11] proposed such a framework when he wrote about sequences of entropy reduction. Aunger's [3] systems theoretical approach in terms of energy innovation, organization and control is also a higher-level approach. Valentin Turchin [58] also proposed a cybernetic theory of complexity transitions with the central concept of *metasystem transition.* Theoretical computer science measures such as *algorithmic complexity* (see e.g. [22]) or *logical depth* [8] are also precious tools to assess the complexity of systems in a universal manner. But these are just a few examples of frameworks to tackle the general, fascinating and fundamental problems of the evolution and measure of complexity (see also [7] for a discussion in the context of Artificial Life).

We already saw that higher outcomes $f_l \cdot f_i$ are harder to assess. This is precisely where computer simulations can be very helpful. Typically, there are so many local interactions in the evolution of complex organisms that it is hard to analyze them analytically with a deterministic science approach. For example, there is not one single equation which allows to predict the development of an embryo.

Let us now outline some remarkable alternative complex universes that researchers recently studied. Gordon McCabe studied variations on the standard model of particles, by changing the geometrical structure of space-time. The result is not the end of any complexity, but just the beginning of a new set of elementary particles. McCabe ([38], 2:38) elaborates:

> Universes of a different dimension and/or geometrical signature, will possess a different local symmetry group, and will therefore possess different sets of possible elementary particles. Moreover, even universes of the same dimension and geometrical signature will not necessarily possess the same sets of possible particles. To reiterate, the dimension and geometrical signature merely determines the largest possible local symmetry group, and universes with different gauge fields, and different couplings between the gauge fields and matter fields, will possess different local symmetry groups, and, perforce, will possess different sets of possible particles.

It thus seems that we can vary basic physics parameters without compromising all kinds of cosmic evolution. Who knows what kind of complexity can emerge from this new set of particles?

As an illustration of their framework to define the multiverse, Ellis, Kirchner and Stoeger [23] did examine some parameter variations in Friedmann-Lemaître-Robertson-Walker (FLRW)

models. They found life-allowing regions in a phase space described by the evolution of FLRW models. The fact that they found *regions* and not a *single point* in the phase space shows that there is room for some variation. So it seems that we can vary fundamental geometrical cosmological parameters without precluding the apparition of life.

Harnik, Kribs and Perez [28] constructed a universe without electroweak interactions called the Weakless Universe. They show that by adjusting standard model and cosmological parameters, they are able to obtain:

> a universe that is remarkably similar to our own. This "Weakless Universe" has big-bang nucleosynthesis, structure formation, star formation, stellar burning with a wide range of timescales, stellar nucleosynthesis up to iron and slightly beyond, and mechanisms to disperse heavy elements through type Ia supernovae and stellar mergers.

This is a truly remarkable result because the cosmic outcomes are numerous, relatively high and non trivial. Three factors in the CEE are addressed more or less directly: $N_g \cdot N_S \cdot f_S$. Maybe strong living creatures could live in the weakless universe? This remains to be investigated.

Anthony Aguirre [2] did study a class of cosmological models "in which some or all of the cosmological parameters differ by orders of magnitude from the values they assume in the standard hot big-bang cosmology, without precluding in any obvious way the existence of intelligent life." This study also shows that it is possible to vary parameters widely without obviously harming the emergence of complexity as we know it.

Robert Jaffe, Alejandro Jenkins and Itamar Kimchi [31] pursued a detailed study of possible universes with modified quark masses. They define *congenial* worlds the ones in which the quark masses allow organic chemistry. Again, they found comfortable regions of congeniality.

Fred C. Adams [1] has conducted a parametric survey of stellar stability. He found that a wide region of the parameter space provides stellar objects with nuclear fusion. He concludes that the "set of parameters necessary to support stars are not particularly rare."

An early attempt to explore alternative universes with simulations has been proposed by Victor Stenger [51, 52]. He has performed a remarkable simulation of possible universes. He considers four fundamental constants, the strength of electromagnetism α; the strong nuclear force α_s, and the masses of the electron and the proton. He then analysed "100 universes in which the values of the four parameters were generated randomly from a range five orders of magnitude above to five orders of magnitude below their values in our universe, that is, over a total range of ten orders of magnitude" [52]. The distribution of stellar lifetimes in those universes shows that most universes have stars that live long enough to allow stellar evolution and heavy elements nucleosynthesis. Stenger's initial motivation was to refute fine-tuning arguments, which is why he ironically baptised his simulation "MonkeyGod". The implicit idea is that even a stupid monkey playing with cosmic parameters can create as much complexity as God.

In conclusion, other possible universes are also fine-tuned for some sort of complexity! Those remarkable studies show consistently that *alternative complex universes are possible.* One might object that such explorations do not yet assess the higher complexity factors in the CEE. They do not answer the following key questions: would other interesting complex structures like planetary systems, life, intelligence or technology evolve in those other universes? However, these are only early attempts in conceptualizing and simulating other possible universes, and the enterprise is certainly worth pursuing. The fine-tuning issue could then be seriously tackled, because we would know more and more precisely the likelihood of having our universe as it is, by comparing it to other possible universes. Such pioneering studies are just a beginning, and certainly new studies will come up with more and more complex alternative universes.

6 Summary

Let us now summarize the three main steps necessary to assess how fine-tuned our universe is.

(1) *Define* a space M of possible universes
(2) *Explore* this space
(3) *Assess* the place of our universe in M

Let us review step (1). Our analysis of the historical trends regarding free parameters [64] invites us to start with a *weak variation*, i.e. varying free parameters in physical and cosmological models. Why not vary the laws of physics themselves? It seems a very cumbersome enterprise, because we do not even know how to make them vary (see [59]). It can also be dubious to do so, since the distinction between laws and initial or boundary conditions is fuzzy in cosmology [21].

This suggestion to focus on weak variation makes most sense for the following reasons. First, it is concrete and operational, and has a clear meaning with well established physics. Second, we assume supernatural miracles happening in the middle of cosmic evolution to be—by definition—impossible. We assume there is a consistency and continuity in cosmic evolution. We hypothesize that higher level parameters are ultimately reducible to these physics and cosmic ones. The emergent higher levels occur naturalistically. Of course, this remains to be shown, and for practical purposes we might assume as given such higher level parameters in our studies and simulations. New levels of emergence, new levels of complexity did historically emerge from lower levels, even if complicated top-down causation occurs (see e.g. [22]). Take for example an economic law like the law of supply and demand. It did not and could not exist before the apparition of organized human civilizations. It emerged out of such new organizations. It seems that what we call “natural laws” are simply the result of more and more regular interactions. For example, as the universe cools down, new organizations emerge. Again, it is clear that a few billion years ago, there was no economic laws.

We also need to be more specific to apply probabilities to the ensemble of possible universes, and avoid probabilistic fallacies. For example, we must decide, arbitrarily or not, parameter’s upper and lower bounds. This is necessary for all practical purposes, because we can not explore the parameter space of all parameters varying from $-\infty$ to $+\infty$. We thus need to define the maximum deviation allowed for each parameter.

We must beware of one-factor-at-a-time limitations and paradox. We must also define a probability measure on the parameter space. I refer the reader to [33] and [23] for detailed arguments that measure-theoretical grounds can be specified to assess fine-tuning. It is also crucial to define *cosmic outcomes* to specify the object of fine-tuning we aim to address. Do we talk about fine-tuning for nucleosynthesis? atoms? Stars? Life? Intelligence? Or a more general complexity emergence?

Step (2) requires to explore this space. The simplest exploration is to re-run the tape of *our* universe. But this only tackles the issue of the *robustness* of the universe. If we want to address the fine-tuning issue we must also run and re-run tapes of *other possible universes.* This will bring us insights into how our and other universes are parameter sensitive, and generate complex outcomes. Although we always need good theoretical models to start with, it is necessary to use computer simulations to explore the huge parameter landscape we are talking about. That landscape is not just very big, but really huge. Because we don't want to and do not have the resources to explore the space blindly, it also makes most sense to use simulations to test particular hypotheses and theories. As an application, if we take Lee Smolin's [49] cosmological natural selection theory, and find alternative universes with more black holes (the cosmic outcome under consideration) by tweaking parameters, it is a way to falsify the theory.

The last step (3) is to compare the distribution functions of the cosmic outcomes obtained through simulations, to the space M of possible universes. In other words, we assess the probability to find a universe with outcome O. Note that this is the crucial difference between tackling the robustness and the fine-tuning issue. In robustness analysis, we run multiple times the *same* universe simulation changing only the random dynamical parameters. We compare multiple runs of the same universe. In fine-tuning analysis, we run multiple *different* universe simulations, changing a wide number of parameters. We compare our universe to the set of possible universes. How typical or atypical is our universe in the space of possible universes? The results of such simulation experiments will enable us to answer this question. Ideally, we will be in a position to assess the likelihood or unlikelihood of complexity emergence in the space of possible universes. Even better than assessing specific cosmic outcomes, which might bias us to a universe-centric perspective, we can aim to assess the probability to find universes which display open-ended evolutionary mechanisms leading to ever increasingly complex cosmic outcomes.

To the traditionally trained cosmologist, this enterprise might seem totally unconventional. And it is, because it is a new kind of computational science. This is why we can call it *Artificial Cosmogenesis.* It might also seem out of reach. As I argued elsewhere, since the sheer computational resources grow more than exponentially, this allows us in principle to increase accordingly the complexity and richness of our computer simulations [62].

Additionally, engineers and professional model makers have developed a wide variety of tools to test multiple variables, rarely used in cosmological contexts. Let us just mention of few of them. A starting point is to use the tools of global sensitivity analysis (see e.g. [45]).

These include advanced statistical approaches such as latin hypercube sampling, multivariate stratified sampling or Montecarlo simulations for finding dynamic confidence intervals. Systems dynamics and engineering have also many tools to offer such as phase portraits or probabilistic designs. The classic book by John D. Sterman [54] remains a reference and quite comprehensive introductory book on complex systems modeling and simulations.

Let us now be scrupulous. What is a proof of fine-tuning? Let n be the number of free parameters. We have a logical and statistical version of what a proof of fine-tuning would be:

> **Logical proof of fine-tuning:** *If you vary one parameter, there exists no possible universe generating outcome O by adjusting the* $(n-1)$ *other parameters.*
> Which is equivalent to:
> *if you vary one parameter, there is no way whatsoever that all other possible universes can generate outcome O.*
>
> **Probabilistic proof of fine-tuning:** *If you vary one parameter, adjusting the* $(n-1)$ *other parameters will not make outcome O more likely.*
> Which is equivalent to:
> *if you vary one parameter, there is no way whatsoever that all other possible universes can generate outcome O with a higher probability.*

In sum, you need to have explored the relevant parameter space of possible universes to make serious claims about fine-tuning. Pretty hard to prove! This is even harder for outcomes as advanced as life or intelligence.

Our conclusion is that *fine-tuning for life or intelligence remains a conjecture.* Like in mathematics, we have strong reasons to believe the conjecture is true, but a proof is out of reach and certainly requires a huge amount of work. As a matter of fact, the challenge of simulating possible universes and comparing them is overwhelming. This is why the concept of the cosmic outcome is so important to ease the process. Indeed, we can break down the problem and progress by tackling higher and higher outcomes, with more and more connection between outcomes. We don't need nor can assess all outcomes at once in the CEE. As our understanding, modeling capacities and computational resources increase, we can be more ambitious in simulating more and more as well as higher and higher outcomes in cosmic evolution. I am well aware of the highly ambitious research program that ACosm proposes. However, the good news is that there is work for many generations of scientists. Tomorrow's cosmology is not restricted to empirical observations or highly theoretical models. It is also the science of simulating and experimenting with alternative universes.

7 Conclusion

Up to now, discussions about possible universes were chiefly a metaphysical recreation. We advanced conceptual foundations to study possible universes scientifically, with the help of computer simulations. This approach is needed if we take seriously the thesis of computational irreducibility, namely that most complex systems are theoretically impossible to predict in a deterministic or statistical manner. A more general computational kind of science is needed. We applied this new kind of science to cosmology, to address two key cosmological issues: the robustness of the emergence of complexity, and the fine-tuning of the universe.

We first formulated the issues of defining possible universes, and possible cosmic outcomes (sections 2 and 3).

Based on previous work, we defined a modular "Cosmic Evolution Equation" (CEE). This equation can have many applications to define research agendas in computational cosmology. In particular, to tackle our two issues, we adjusted the CEE by varying the space of possible universes it acts upon, to study either the robustness (section 4) or the fine-tuning issue (5).

Importantly, we considered only a *virtual multiverse*, that we define within our concrete models and simulations. This is in sharp contrast with speculations about an actual multiverse, an idea quite common in modern cosmology, yet often criticized for being hard or impossible to test scientifically.

To address the delicate fine-tuning issue, we further argued that studies and simulations of alternative possible universes are demanded, a research field called *Artificial Cosmogenesis* (ACosm, sections 5-6). This field is actually not new, since we outlined quite some research which have examined alternative possible universes. Yet these studies are really just beginning to explore possible universes, and ACosm holds great promise to further investigate whether and how our universe and others generate increasing complexity.

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A Appendix - Argumentative Maps

Fig. 2 maps the problem described in introduction, while Fig. 3 maps the core argument presented in the paper. Please read in a top-down direction. More details on argumentation mapping can be found in [62].

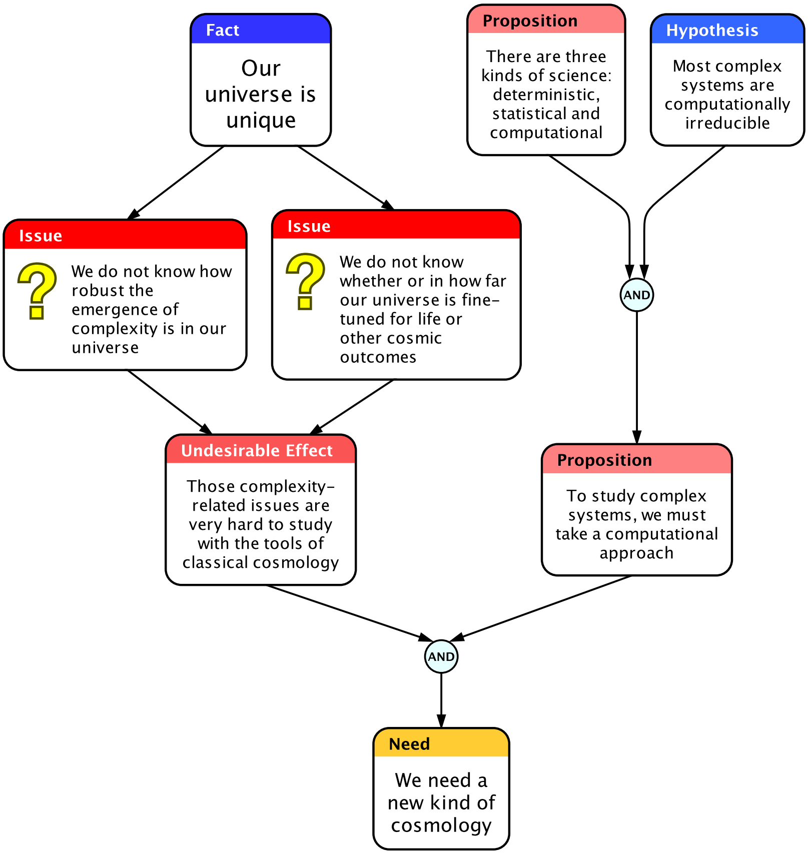

Fig. 2. The core problem

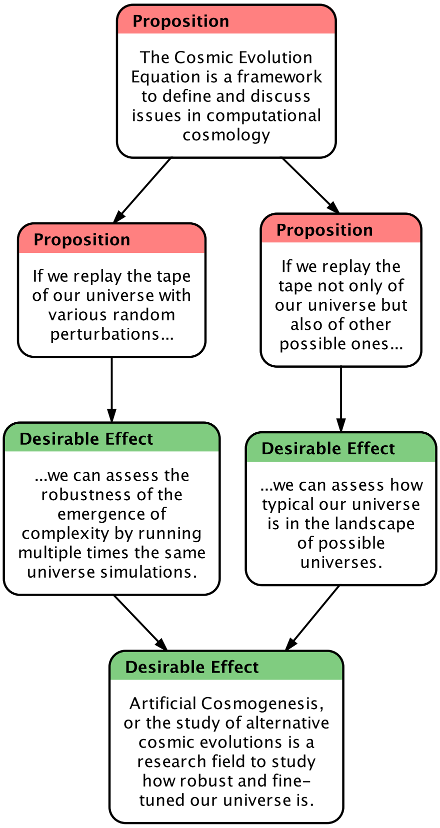

Fig. 3. The proposed solution

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