universe

MDPI

Article

Multiverse—Too Much or Not Enough?

Michael Heller

Copernicus Center for Interdisciplinary Studies ul. Szczepańska 1/5, 31-011 Cracow, Poland; mheller@wsd.tarnow.pl

Received: 15 April 2019; Accepted: 9 May 2019; Published: 11 May 2019

Abstract: The aim of this essay is to look at the idea of the multiverse—not so much from the standpoint of physics or cosmology, but rather from a philosophical perspective. The modern story of the multiverse began with Leibniz. Although he treated "other worlds" as mere possibilities, they played an important role in his logic. In a somewhat similar manner, the practice of cosmology presupposes a consideration of an infinite number of universes, each being represented by a solution to Einstein's equations. This approach prepared the way to the consideration of "other universes" which actually exist, first as an auxiliary concept in discussing the so-called anthropic principle, and then as real universes, the existence of which were supposed to solve some cosmological conundrums. From the point of view of the philosophy of science, the question is: Could the explanatory power of a multiverse ideology compensate for the relaxation of empirical control over so many directly unobservable entities? It is no surprise that appealing to a possibly infinite number of "other universes" in order to explain some regularities in our world would seem "too much" for a self-disciplined philosopher. With no strict empirical control at our disposal, it is logic that must be our guide. Also, what if logic changes from one world to another in the multiverse? Such a possibility is suggested by the category theory. From this point of view, our present concepts of the multiverse are certainly "not enough". Should this be read as a warning that the learned imagination can lead us too far into the realms of mere possibilities?

Keywords: multiverse; Leibniz; other worlds; multiverse levels

---

Or, had I not been such a commonsensical chap, I might be defending not only a plurality of possible worlds, but also a plurality of impossible worlds, whereof you speak truly by contradicting yourself.
David Lewis

1. Introduction

The editor of the volume *Universe or Multiverse?* makes a funny, albeit fully justified, remark: "The word 'multiverse' is always spelt [in this volume] with a small 'm', since . . . there could be more than one of them". How so? Because "the idea arises in different ways" ([1] p. XV). Indeed, ideas arise in many ways. The origin of some of them almost goes back to prehistory, where some evolve slowly through the ages, and some are brought to life by the sudden illumination of a genius. None of these ways gave birth to the idea of a multiverse.[1] It emerged long before it was named—first in poetry and fairy tales, then in philosophy, and has only recently appeared on the fringes of science. This was originally to dramatise the "extreme improbability" of some events, where it then emerged soon after as a real possibility, founding itself at the heart of a heated discussion. Some see in this idea the beginning of a new era in the philosophy of science, whereas others regard it as a serious danger to well-established methods that have, so far, guaranteed the greatest success.

[1] In this essay, all "multiverses" and "universes" will be democratically written with small letters.

In this essay (just an essay, not a systematic study), I want to look at the recent adventures (to use Whitehead's phrase) of the multiverse idea—though not so much from the standpoint of contemporary physics or cosmology, but rather from a philosophical perspective. If there are problems with the empirical control of the multiverse models, we should examine their explanatory power. In all these questions, the philosophy of science has something to say. However, we should not forget that the standard philosophy of science has never previously encountered postulated entities in physics which are so distant from any empirical control.

Suppose we have decided to leave the secure region of scientific methodology; then why not go even further into the domains suggested by the developments of mathematics? After all, if the empirical criteria are relaxed, it is only mathematics that remains as our guide, and the mathematical category theory says that even logic can change from one category to another. Should we not take into account the variability of logic in creating "other universes"? From this point of view, our present thinking about multiverses is certainly inadequate.

My way of thinking about these matters will be organised along the following lines. The modern story of the multiverse began with Leibniz. Although he treated "other worlds" as mere possibilities, they played an important role in both his theodicy and his logic (Section 2). In a similar manner, doing cosmology presupposes the consideration of an infinite number of universes, each being represented by a solution to Einstein's equations. This is a non-controversial version of a multiverse, also called an "ensemble of universes" (Section 3). This approach prepared the way to considering "other universes" which actually exist—first as an auxiliary concept in discussing the so-called anthropic principle, and then as real universes, the existence of which were supposed to solve some important cosmological conundrums (Section 4). From the point of view of the philosophy of science, one should ask the following question: Could the explanatory power of a multiverse ideology compensate for the relaxation of the empirical control over so many directly unobservable entities? It is unsurprising that an appeal to a great, perhaps infinite number of "other universes" in order to explain some regularities in our world, must seem "too much" for the orderly philosopher (Section 5). One should agree that without strict empirical control, it is logic and mathematics that must be our guide. And what if logic changes from one world to another in the multiverse? Such a possibility is suggested by the category theory, which is, today, unavoidable in any consideration of the foundations of mathematics, and consequently of physics as well. From this point of view, our present concepts of the multiverse are certainly "not enough" (Section 6). This is a challenge, but could also be read as a warning that the imagination—even the learned imagination—can lead us too far into the realms of mere possibilities.

2. A Philosopher's Paradise

The great story of the multiverse began with Leibniz. When he ordered his God to create the best of possible worlds, he automatically urged him to make some calculations on the set of all possible universes. However, the "all possible worlds" ideology is interesting, not only as far as Leibniz's own philosophical views are concerned. Only some minor intellectual gymnastics need be exercised to show that his doctrine of possible worlds foreshadows the modal semantics of the twentieth century [2].

Modal logic is a chapter of logic in which, besides the usual connectives (implication, negation, etc.) of classical propositional calculus, the functors "it is necessary that" and "it is possible that" are considered. The point is that whereas propositional calculus is extensional, modal logic is intensional. An extension of a term is the set of things to which the term applies; intension of a term involves its meaning. There is a serious problem on how to define semantics for modal logic—that is, "a theory that provides rigorous definitions of truth, validity, and logical consequence for the language" [3]. A solution was suggested by Carnap [4], and developed by Lewis [5] and others. The solution is as follows:

- A sentence is *necessarily* true if, and only if, it is true in every possible world.
- A sentence is *possibly* true if, and only if, it is true in some possible worlds.

In this way, modal logic did not become extensional, but it receives extensional semantics. Lewis did not hesitate to write: "As the realm of sets is for mathematicians, so logical space is a paradise for philosophers. We have only to believe in the vast realm of possibilia, and there we find what we need to advance our endeavours" ([3] p. 4).

3. A Context for Cosmology

Something similar happened in a field of research very distant from logical semantics—that is, cosmology. It turned out that the study of possibilities is essential for the study of the actual universe. To see this, let us start with something that seems to indicate precisely the opposite.

It is commonplace to declare that the peculiarity of cosmology as a science stems from the fact that the object of its study "is given to us in a single copy". This was most eloquently expounded by Bondi in his classic textbook ([6] pp. 9–10): "In physics we are accustomed to distinguish between the accidental and the essential aspects of a phenomenon by comparing it with similar phenomena. . . . The uniqueness of the actual universe makes it impossible to distinguish, on purely observational grounds, between its general and its peculiar features, even if such a distinction were logically tenable. . . . In either case, we select the important (as opposed to the 'accidental') features of the actual universe by their relation to the theory chosen rather than by any independent criterion". How do we do that? By artificially multiplying the object of our study. Let us take a closer look at this strategy.

For the empirical method, it is essential to have many instances of objects under investigation. The laws of physics are usually formulated in the form of differential equations, which describe general dependencies between the properties of a given class of phenomena, whereas individual characteristics of phenomena are accounted for by selecting initial or boundary conditions, and identifying a particular solution. Also, the very idea of measurement presupposes many copies of the measured object. Because of unavoidable measurement errors, we never refer to a single measurement result, but rather to their class within the box of errors. In this way, we are not dealing with a single object, but rather with a class of objects, only slightly differing from each other. This strategy in cosmology assumes the following form. We (tacitly) assume that the actual universe is described (up to a reasonably good approximation) by a solution to Einstein's field equations, and that any other of its solutions describes a possible universe. Our measurements never single out a unique solution, but rather a class of "nearby" solutions. In this way, the actual universe is placed "in the context" of other universes.

Moreover, in cosmology, this strategy has been exploited in a systematic manner and expanded to the form of a specialized field of research. The space of all solutions to Einstein's equation has even merited a special name: the *ensemble of universes* (or the *ensemble*, for short). This space is extremely rich—so rich that usually only some of its rather restricted subspaces are subject to investigation. For instance, the space of solutions with no symmetries to vacuum Einstein's equations is a smooth, infinite-dimensional manifold, but in the neighbourhood of a solution with symmetries, the smoothness breaks down and a conical singularity intervenes [7].[2]

As we have mentioned above, the very problem of measurement compelled us to consider "nearby solutions". This is also true as far as some not directly observable properties of solutions are considered—for instance, initial conditions leading to inflation, the existence of singularities or horizons. Claiming that the solution has such a property presupposes its *structural stability*. Roughly speaking, a property is said to be structurally stable if it is shared by all "nearby" solutions.[3] Structurally unstable properties are not considered to be realistic. The problem at stake is by no means

[2] In general, the space of solutions to the vacuum Einstein equations is a smooth infinite-dimensional manifold. However, in a neighbourhood of a solution with symmetries (it is enough for a solution to have a single Killing vector field) the solutions cannot be parametrised in a smooth way by elements of a linear space. In other words, at such a solution there is no tangent space to the space of solutions; just as there is no tangent space at the vertex of a cone.

[3] Structural stability is, in principle, a property of a dynamical system. It says that small perturbations do not affect the qualitative behaviour of nearby trajectories. In many cases, solutions to Einstein equations can be represented as trajectories of a dynamical system.

trivial. To meaningfully define structural stability (with respect to a given property), one should know which solutions are to be regarded as equivalent ("identical"), and when the distance between two non-equivalent solutions is to be regarded as "small". To this end, the space of solutions must be equipped with a suitable topology, and this is a tricky task which has been elaborated only with respect to some properties (e.g., for space-times that are stably causal [8,9][4]).

We can conclude that the ensemble of universes is a natural environment or a context for cosmology; one could even claim that theoretical cosmology is but a theory of the ensemble ([10] pp. 70–76).

4. Multiverses (In Plural)

From what is natural to what exists is but a small step. Over recent decades, it has become fashionable to look for answers to some deep questions, both from the fields of cosmology and metaphysics, by claiming that a large, possibly even an infinite, number of universes exists. The name "multiverse" was coined for such a huge collection of worlds. One of the first signals that such a fashion was approaching was Brandon Carter's idea of an "ensemble of universes"[5], which he referred to in the context of the so-called anthropic principles [11]. In Carter's intention, it served only as a means to dramatise the situation he was talking about. The drama consisted of the fact that the subset of universes in which observers can exist is extremely small: "Any organism describable as an observer will only be possible within a certain restricted combinations of parameters", and consequently, extremely "improbable" to be established by chance. What was a heuristic picture for Carter, soon became a postulated reality—if any combination of cosmological parameters is implemented somewhere within the ensemble of universes, then the observer permitted by such a combination must also be implemented somewhere, and in this way, "small probability" and "chance" are smoothly eliminated.

The contemporary defenders of the multiverse idea emphasize that this line of reasoning is now, at most, an auxiliary argument on behalf of this idea[6], and that the authentic arguments stem from the fact that the concept of a multiverse emerges, as a kind of side effect, from several physical theories or models. In this sense, it is almost unavoidable. As explained by George Ellis: "It has been claimed that a multi-domain universe is the inevitable outcome of physical processes that generated our own expanding region from a primordial quantum configuration; they would therefore have generated many other such regions" ([12] pp. 387–388). Although he directly refers only to multi-domain universes,[7] the same remains valid, more or less, as far as other types of multiverses are concerned.

Brian Green organizes his best-selling book *The Hidden Reality* [13] around nine types of multiverses (not limiting himself only to those that are implied by some physical theories or models). They are:

1. The multi-domain multiverse: Alluded to by Ellis.[8]
2. The inflationary multiverse: Eternal cosmological inflation leading to innumerable generations of bubble universes.
3. The brane multiverse: This is an outcome of the M-theory.
4. The cyclic multiverse: Collisions between branes producing big bangs separating subsequent universes.
5. The landscape multiverse: A combination of inflationary cosmology with string theory.

---

[4] Strictly speaking, in this context it is not the space of solutions of Einstein's equations that is taken into account, but rather the space of all Lorentz metrics, only some of them could be solutions to Einstein's equations.
[5] Not to be confused with the "ensemble of universes" as the space of solutions to Einstein's equations.
[6] This does not mean, however, that it disappears from cosmological texts; on the contrary, references and longer debates abound.
[7] By a multi-domain universe, Ellis understands an infinite universe in which very far-away space-time domains are regarded as separate universes.
[8] Green claims that in an infinite universe the same "local universe" must replicate itself across space.

6. The quantum multiverse: This is implied by the realistically understood many-worlds interpretation of quantum mechanics.
7. The holographic multiverse: Stems from the hypothesis that the entire universe can be viewed as information on the two-dimensional cosmological horizon.
8. The simulated multiverse: That is, simulated by a supercomputer.
9. The ultimate multiverse: All mathematical structures are instantiated as real universes.

This catalogue can hardly be regarded as complete; for instance, it does not include Penrose's cyclic universe [14]. Such a proliferation of multiverses poses the question of the observational verification of theories that claim their existence. The situation appears dramatic: "Cosmology will only ever get one horizon-full of data. Our telescopes will see so far, and no further. At any particular time, particle accelerators reach to the finite energy scale, and no higher" [15]. The problem is, therefore, about the "inference beyond data" [16]. In their heroic attempts to solve this problem, people use various strategies, frequently turning for help to Bayesian Probabilistic methods.

Although multiverse models are resistant with respect to verification, some of them could offer some hope as far as falsification is concerned (at least in principle). For instance, suppose that a multiverse model predicts that every member of the ensemble of possible universes should share a certain feature (for example, a negative cosmological constant). If this was not observed, this particular model would be falsified. However, in standard physics, falsification of theories is always made, at least implicitly, in the hope that this could help in selecting the right theory, whereas in the case of the multiverse, such a hope is practically non-existent.

5. It Is Too Much

The problem of the unobservable entities that are presupposed by physical theories (their linguistic counterparts are called theoretical terms) is an old problem in the philosophy of science. The works of Carnap [17] and Ramsey [18] (for a review, see [19]) are classic in this respect. However, the situation with multiverses is somewhat different. In classic discussions on the topic, theoretical terms referred to such entities like electrons and neutrons at that time were unobservable but had observable consequences, whereas in the present debate, we have in mind parallel universes that are causally totally disconnected from us. The number of such universes is usually assumed to be infinite, or at least extremely large[9]. In this context, Tavakol and Gironi [20] speak about the infinite turn in contemporary cosmology.

Today, nobody denies scientific theories the right to bring to life theoretical (not directly observable) terms, although their ontological status is an object of highly divergent opinions. Those who adhere to some kind of scientific realism are prone to agree that theoretical terms might correspond to some really existing objects, "provided that theory under consideration is *currently complete*, i.e., capable of unambiguously accounting for the current observations in its domain of applicability, as well as making novel testable predictions" ([20] p. 786). No single theory invoked to justify the existence of a multiverse is complete in this sense. Therefore, if we use the multiverse idea to explain some puzzling data in cosmology, we are, in fact, using an "explanation by unexplained" strategy. To quote the same authors: "The aim of a cosmological explanation should be that of providing a deeper understanding of the Universe, but the Multiverse type scenario rather shifts the target of the explanatory task from the finite observed Universe to a postulated relative or real infinite 'Landscape"' ([20] p. 793)[10]. This consequently opens up a new question about the explanatory power of the multiverse idea.

---

9 Although a multiverse consisting of a finite number of universes is in principle possible, it seems rather artificial.
10 Capitalized by the quoted authors.

Once again, the problem of explanation is a frequently discussed problem in the philosophy of science (see, e.g., [21,22]). Very roughly, philosophers distinguish two main types (or models) of explanations: deductive-nomological explanations and causal explanations.

According to the first type, also called Hempel's model (or the Hempel-Oppenheim model, or the Popper-Hempel model) of explanation, a phenomenon is explained if a sentence describing it (*explanandum*) is deduced from a set of true sentences (*explanans*), among which there is at least one law of nature. The first (deductive) part of this model could somehow be adapted to the multiverse situation: some properties of our universe could be deduced from some properties of a multiverse (not necessarily in the logico-linguistic manner, preferred by Hempel, but rather in the form of probabilistic inferences). Whether the second (nomological) part of the explanation model refers to a given multiverse depends on how it is conceived.

As far as the causal model of explanation is concerned, there exists tremendously rich literature (see, for instance, the often-quoted [23–25]), and such a variety of approaches, that even a short review of them would exceed the limits of this study. However, I feel free from this responsibility, since causal explanations hardly apply to our case. I will mention only one proposal which could be of some relevance at least to some versions of multiverse. I have in mind Wesley Salmon's proposal, which he calls the causal mechanical model of explanation [25]. He considers physical processes and distinguishes "pseudo-processes from genuine causal processes". The motion of a material object or the propagation of a sound wave through space are genuine causal processes, whereas a moving shadow is a pseudo-process, since it cannot transmit causal interactions. In his opinion, "a process is causal if and only if it has the capacity to transmit a mark". A mark or signature is a local modification or perturbation in the process that can be transmitted further by this process [26]. In some versions of multiverses, such a signature is indeed claimed to be transmitted to our universe. For instance, in the model of chaotic inflation, one considers the possibility that "baby universes", which nucleated from our universe and then collided with it, could have impressed a trace in the microwave background radiation in our universe (see, e.g., [27]). With respect to all other multiverse models, causal explanations simply do not work.

The standard answer to the above criticism usually given by defenders of the multiverse philosophy is to say that all the above objections are based on the old-fashioned philosophy of science, whereas the multiverse approach opens a new paradigm. If so, this new paradigm would apply only to some unsolved problems of cosmology and fundamental physics, since any relaxation of strict empirical constraints in all other branches of physics would be disastrous.

6. It is Not Enough

As we have remarked above, all theories giving rise to multiverses are incomplete. Therefore, it cannot be excluded that the future complete (or at least, "more complete") theory of fundamental physics will compel us to introduce some changes into the very concept of the multiverse. It is worthwhile asking to what extent the present concepts of multiverse are "stable" with respect to future developments in physics. Of course, the full answer to this question can only be provided by what will happen in the real future. Let us, however, permit ourselves the following thought experiment.

John Baez, a physicist of considerable renown, confesses that, motivated by the diversity of approaches to the search for a "final theory", he has decided, for now, to suspend his work on loop quantum gravity and to "re-examine basic assumptions and seek fundamentally new ideas". This has led him to the program of the categorification of physics [28]. It follows the program of the categorification of mathematics, which has been intensively pursued for some time. It seems reasonable to ask how the categorification of physics could modify our views on the multiverse idea. In trying to tackle this question, I shall not go into the details of the categorification program itself, but rather focus on one, possibly unavoidable, consequence. To see the extent of this consequence, we must first take a look at the connection between the category theory and logic.

The crucial point is that any sufficiently rich category[11] has its internal logic, in the sense that any such category can be used to construct a model for a certain logical system and, *vice versa*, one can extract a logical system out of any sufficiently rich category. The strongest such logical system constitutes the internal logic of this category. These intuitions can be made precise (see [29] or for a short review [30]). For instance, all of the axioms of intuitionistic logic are satisfied[12] in any topos[13]; however, the internal logic of a topos can be stronger than (first-order) intuitionistic logic (depending on the internal architecture of a given topos). Analogously, any complementary topos (also called cotopos) satisfies all of the axioms of paraconsistent logic[14], and the axioms of classical logic are satisfied in the category denoted by SET (which has sets as objects, maps between sets as morphisms, and all set theoretic axioms are expressed in the language of morphisms).

This strict connection between category theory and logic gives a new insight into the role of category theory as a unifying framework for the whole of mathematics. The fact that dependencies between different mathematical theories can be presented with the help of functors[15], and functors between functors, is now common knowledge, but the consequences of the fact that logic is not a sovereign ruling the entire affair from above, but rather a factor strongly involved in the game itself, is something that only laboriously, but irrevocably, emerges. Moreover, the same mathematical theory can be viewed from different "categorical frames". This motivated John Bell to propose a "local interpretation of mathematics". In his words: "With the relinquishment of the absolute universe of sets, mathematical concepts will in general no longer possess absolute meaning, nor mathematical assertions absolute truth values, but will instead possess such meanings or truth values only *locally*, i.e., *relative* to local frameworks"[16] [33].

Can these developments have repercussions in physics? Obviously, the standard macroscopic physics is conducted in the "framework" of SET, but the fact that quantum mechanics presupposes a not-quite-classical logic (the so-called quantum logic) signals that logic could be a "physical variable", meaning it could change depending on a physical theory (in the spirit of Bell's interpretation). The categorical approach to physics, although it is, at present, on the introductory level, reveals an intricate role that logic seems to play in physical theories. It is classical logic that has been abstracted from our everyday experience, but there is no guarantee that the same logic is adequate for all levels of reality. In this respect, the category theory offers entirely new possibilities. Logical tools of analysis are not to be employed from outside, but rather, to work within the physical theory as an aspect of its own structure.[17] This possibility should be taken seriously, especially as far as the candidates for a "final" physical theory are concerned.

As far as I know, all concepts of the multiverse now in circulation are (tacitly) assumed to function within the SET category (perhaps with the exception of Max Tegmark's idea that all mathematical structures are somewhere implemented as "other universes", but to say this is not to say much) and, in light of the above, this is an abject limitation. If we admit "all possibilities", we should not

---

[11] A quick reminder: A category consists of a collection of objects and a collection of morphisms (also called arrows) between objects. Morphisms can be composed (provided the head of one arrow coincides with the tail of the other arrow), and the composition of morphisms is associative. There exist identity morphisms satisfying the usual identity axioms. Richness of categories is enormous: from simple ones (like the category consisting of a single object and a single identity morphism) to categories covering large areas of mathematics.

[12] Intuitionistic logic is the one in which the excluded middle law (p or not p) is not valid and the axiom of choice cannot be used; see [31].

[13] Topoi (or toposes) form a class of categories especially related to the theory of sets. Although a topos can contain objects that are much richer and considerably different from sets, the abstract categorical properties of topoi are essentially the same as those known from the theory of sets; see [31].

[14] Paraconsistent logic is, in a sense, dual with respect to intuitionistic logic; in it the noncontradiction law (it is not true that p and not p) is not valid; see [32].

[15] A functor transforms one category into another category (objects into objects, morphisms into morphisms) in such a way that all defining axioms are preserved.

[16] By the term "local framework" Bell understands a topos with an object of natural numbers.

[17] For the role of category theory in physics, see [34].

impose arbitrary limits. Imagine a multiverse based on all of the consequences of the category theory, with logic changing from one world to another! What a paradise for a gifted mathematician!

In the above remarks, I have taken into account only ordinary categories (1-categories), and what about n-categories and their internal logic? And why exclude the category of all categories? Who said that the logic—our poor classical logic—inscribed by evolution into our brains, is able of comprehending everything that exists? Indeed, multiverses, as we consider them now, are not enough.

Would this idea somehow help us to practice physics, which is wretchedly restricted to the visible horizon of our local universe? This is another story.

Funding: This publication was made possible through the support of a grant from the John Templeton Foundation (Grant No. 60671).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Carr, B. (Ed.) *Universe or Multiverse*; Cambridge University Press: Cambridge, UK, 2007.
2. Look, B.C. Leibniz's Modal Metaphysics. In *Stanford Encyclopedia of Philosophy*. 2013. Available online: https://plato.stanford.edu/entries/leibniz-modal (accessed on 23 June 2018).
3. Manzel, C. Possible Worlds. In *Stanford Encyclopedia od Philosophy*. 2017. Available online: https://plato.stanford.edu/entries/possible-worlds (accessed on 23 June 2018).
4. Carnap, R. *Meaning and Necessity*; The University of Chicago Press: Chicago, IL, USA, 1947.
5. Lewis, D. *On the Plurality of Worlds*; Blackwell: Oxford, UK, 1986.
6. Bondi, H. *Cosmology*; Cambridge University Press: Cambridge, UK, 1960.
7. Fisher, A.E.; Marsden, J.E.; Moncrief, V. Symmetry Breaking in General Relativity. In *Essays in General Relativity. A Festschrift for Abraham Taub*; Tipler, F.J., Ed.; Academic Press: New York, NY, USA; London, UK, 1980; pp. 79–96.
8. Hawking, S.W. Stable and Generic Properties in General Relativity. *Gen. Relativ. Gravit.* **1971**, *1*, 393–400. [CrossRef]
9. Hawking, S.W.; Ellis, G.F.R. *The Large Scale Structure of Space-Time*; Cambridge University Press: Cambridge, UK, 1973.
10. Heller, M. *Theoretical Foundations of Cosmology*; World Scientific: Singapore; London, UK, 1992.
11. Carter, B. Large Number Coincidences and the Anhropic Principle in Cosmology. In *Confrontation of Cosmological Theories and Observational Data (IAU Symposium)*; Longair, M., Ed.; Reidel: Dordrecht, The Netherlands, 1974; pp. 281–289.
12. Ellis, G.F.R. Multiverses: Description, Uniqueness and Testing. In *Universe or Multiverse?* Carr, B., Ed.; Cambridge University Press: Cambridge, UK, 2007; pp. 387–409.
13. Greene, B. *The Hidden Reality*; Vintage Books: New York, NY, USA, 2011.
14. Penrose, R. *Cycles of Time*; The Bodley Head: London, UK, 2010.
15. Barnes, L.A. Testing the Multiverse; Bayes, Fine-Tuning and Typicality. In *The Philosophy of Cosmology*; Chamcham, K., Silk, J., Barrow, J.D., Saunders, S., Eds.; Cambridge University Press: Cambridge, UK, 2017; pp. 447–466.
16. Sahlén, M. On Probability and Cosmology: Inference Beyond Data? In *The Philosophy of Cosmology*; Chamcham, K., Silk, J., Barrow, J.D., Saunders, S., Eds.; Cambridge University Press: Cambridge, UK, 2017; pp. 429–446.
17. Carnap, R. *Philosophical Foundations of Physics: An Introduction to the Philosophy of Science*; Basic Books: New York, NY, USA, 1966.
18. Ramsey, F.P. Theories. In *Foundations. Essays Philosophy, Logic, Mathematics and Economics*; Mellor, H.D., Ed.; original edition in 1929; Routledge and Kegan Paul: London, UK, 1978; pp. 101–125.
19. Holger, A. Theoretical Terms in Science. In *The Stanford Encyclopedia of Philosophy*; Zalta, E.N., Ed.; 2017. Available online: https://plato.stanford.edu/archives/fall2017/entries/theoretical-terms-science (accessed on 23 June 2018).
20. Tavakol, R.; Gironi, F. The Infinite Turn and Speculative Explanations in Cosmology. *Found. Sci.* **2017**, *22*, 785–798. [CrossRef]

21. Skow, B. Scientific Explanation. In *The Oxford Handbook of Philosophy of Science*; Humphreys, P., Ed.; Oxford University Press: Oxford, UK, 2016; pp. 525–543.
22. Woodward, J. Scientific Explanation. In *The Stanford Encyclopedia of Philosophy*; Zalta, E.N., Ed.; 2017. Available online: https://plato.stanford.edu/archives/fall2017/entries/scientific-explanation (accessed on 23 June 2018).
23. Woodward, J. *Making Things Happen: A Theory of Causal Explanation*; Oxford University Press: Oxford, UK, 2003.
24. Lewis, D. Causal Explanation. In *Philosophical Papers*; Oxford University Press: New York, NY, USA, 1986; Volume II, pp. 214–240.
25. Salmon, W. *Scientific Explanation and the Causal Structure of the World*; Princeton University Press: Princeton, NJ, USA, 1984.
26. Salmon, W. The Causal Structure of the World. *Metatheoria* **2010**, *1*, 1–13.
27. Johnson, M.C.; Peiris, H.V.; Lehner, L. Determining the Outcome of Cosmic Bubble Collisions in Full General Relativity. *Phys. Rev. D* **2012**, *85*, 083516. [CrossRef]
28. Baez, J. Categoryfying Fundamental Physics. Available online: http://math.ucr.edu/home/baez/diary/fqxi_narrative.pdf (accessed on 20 June 2018).
29. Lambek, J.; Scott, P.J. *Introduction to Higher Order Categorical Logic*; Cambridge University Press: Cambridge, UK, 1994.
30. Fu, Y. Category Theory, Topos and Logic: A Quick Glance. Available online: http://charlesfu.me/repository/topos.pdf (accessed on 29 September 2015).
31. Goldblatt, R. *Topoi. The Categorical Analysis of Logic*; Dover Publications: Mineola, NY, USA, 2006.
32. Estrada-González, L. Complement-Topoi and Dual Intuitionistic Logic. *Aust. J. Log.* **2010**, *9*, 26–44. [CrossRef]
33. Bell, J.L. From Absolute to Local Mathematics. *Synthese* **1986**, *69*, 409–426. [CrossRef]
34. nLab. Higher Category Theory and Physics. Available online: https://ncatlab.org/nlab/show/higher+category+theory+and+physics (accessed on 23 June 2018).