Epistemology of String Theory in Quantum Gravity

Nicolae Sfetcu

24.10.2019

Sfetcu, Nicolae, " Epistemology of String Theory in Quantum Gravity", SetThings (October 24, 2019), URL = https://www.setthings.com/en/epistemology-of-string-theory-in-quantum-gravity/

Email: nicolae@sfetcu.com

A partial translation of
Sfetcu, Nicolae, "Epistemologia gravitației experimentale – Raționalitatea științifică", SetThings (1 august 2019), MultiMedia Publishing (ed.), ISBN: 978-606-033-234-3, DOI: 10.13140/RG.2.2.15421.61925, URL = https://www.setthings.com/ro/e-books/epistemologia-gravitatiei-experimentale-rationalitatea-stiintifica/

BIBLIOGRAPHY 11

In quantum field theory, the main obstacle is the occurrence of the untreatable infinities in the interactions of the particles due to the possibility of arbitrary distances between the point particles. Strings, as extended objects, provide a better framework, which allows finite calculations.[1] String theory is part of a research program in which point particles in particle physics are replaced by one-dimensional objects called strings. It describes how these strings propagate through space and interact with one another. At larger scales, a string looks like an ordinary particle, with mass, charge and other properties determined by the vibrational state of the string. One of the vibrational states of the strings corresponds to graviton, the hypothetical particle in quantum mechanics for gravitational force.[2] String theory is usually manifested at very high energies, such as in black hole physics, early universe cosmology, nuclear physics, and condensed matter physics. String theory tries to unify gravity and particle physics, and its later versions try to modify all the fundamental forces in physics.[3]

The purpose of string theory was to replace elementary particles with one-dimensional strings in order to unify quantum physics and gravity.

The string theory research program is based on a 1930 assumption that general relativity resembles the theory of a field of spin-two without mass in the Minkowskian flat space.[4] The quantification of such a theory has been shown not to be perturbative renormalizable, implying infinities that cannot be eliminated. This early theory was abandoned until the mid-1970s, when it was developed as a one-dimensional string theory.

It should be noted that the string theory was initially developed, in the late 1960s and early 1970s in particle physics - the bosonic string theory, which only dealt with bosons. After a temporary success as a hadron theory, quantum chromodynamics has been recognized as the correct hadron theory. In 1974 Tamiaki Yoneya discovered that the theory provides a massive particle of spin 2, considered to be a graviton. John Schwarz and Joel Scherk reintroduced Kaluza-Klein's theory for additional dimensions, recovered the abandoned bootstrap program, and thus began the string theory research program in quantum gravity. A typical example of reinvigorating a research program in the sense of Lakatos (bootstrap program) and changing the direction of research of another program (string theory) whose heuristics, by adding an additional theory (Kaluza-Klein), has proved to be a lot more useful in a different direction than originally envisaged. Later it was developed in the *superstring theory*, based on the

---

[1] Richard Dawid, "Scientific Realism in the Age of String Theory," *Physics and Philosophy*, 2007.

[2] Katrin Becker, Melanie Becker, and John H. Schwarz, *String Theory and M-Theory: A Modern Introduction* (Cambridge ; New York: Cambridge University Press, 2007), 2–3.

[3] Becker, Becker, and Schwarz, 3, 15–16.

[4] A. Capelli, "The Birth of String Theory Edited by Andrea Cappelli," Cambridge Core, April 2012, https://doi.org/10.1017/CBO9780511977725.

supersymmetry between bosons and fermions,[5] and then appeared other versions of the theory. In the mid-1990s, scientists focused on developing a unifying research program, an eleven-dimensional theory called the *M theory*.

The strings do not have quantum numbers, but they differ in their topological form (open or closed, modes of compacting) and their dynamics (modes of oscillation). They can be perceived on a macroscopic scale as point particles with certain quantum numbers. The change of the oscillation mode corresponds to a transformation to another particle. The strings at the fundamental level do not have coupling constants. The interaction between them corresponds to their dynamics.[6]

For each version of string theory there is only one type of string, such as a small loop or string segment, which can vibrate in different ways. In the string theory research program, the characteristic string length scale is of the order of Planck length (10^{-35} meters), over which the effects of quantum gravity are considered significant.[7] At ordinary dimensions, such objects cannot be distinguished from zero-dimensional point particles. There are several variants of the superstring theory: type I, type IIA, type IIB and two types of heterotic strings, SO (32) and E8×E8.

String theories require additional dimensions of spacetime for mathematical consistency. In bosonic string theory, spacetime is 26-dimensional, while in superstring theory it is 10-dimensional, and in M-theory it is 11-dimensional. These additional dimensions will not be observed in experiments,[8] due to their compaction by which they "close" on themselves forming circles. At the limit, when these extra dimensions tend to zero, they reach the usual spacetime. In order for the theories to properly describe the world, the compacted dimensions must be in the form of the Calabi-Yau manifolds.[9]

Another way to reduce the number of dimensions is by using the membrane cosmology scenario (“brane-world”), considering the observable universe as a three-dimensional subspace of a multi-dimensional space. In these models, gravity appears from the closed strungs in a space with several dimensions, thus explaining the lower power of gravity compared to the other fundamental forces.[10] In string theory, a *brane* (the abbreviation for "membrane") generalizes

---

[5] Becker, Becker, and Schwarz, *String Theory and M-Theory*, 4.

[6] Vincent Lam, “Quantum Structure and Spacetime.,” *Metaphysics in Contemporary Physics*, January 1, 2016, 81–99, https://doi.org/10.1163/9789004310827_005.

[7] Becker, Becker, and Schwarz, *String Theory and M-Theory*, 6.

[8] Barton Zwiebach, *A First Course in String Theory*, 2 edition (Cambridge ; New York: Cambridge University Press, 2009).

[9] Shing-Tung Yau, *The Shape of Inner Space*, Reprint edition (Basic Books, 2012), chap. 6.

[10] Lisa Randall and Raman Sundrum, “An Alternative to Compactification,” *Physical Review Letters* 83, no. 23 (December 6, 1999): 83 (23): 4690–4693, https://doi.org/10.1103/PhysRevLett.83.4690.

the notion of a point particle to dimensions other than zero. Branes are physical bodies that obey the rules of quantum mechanics.[11]

A particularity of the theories in this research program are the "dualities", mathematical transformations that identify the physical theories within this program between them, drawing the conclusion that all these theories are subsumed into one, the M-theory.[12] Two theories are dual if they are exactly equivalent in terms of observational consequences, although they are constructed differently and may involve different objects and topological scenarios.[13] The different theories within the string theory research program are linked by several relationships, one being the specific correspondence relation called duality S.[14] Another relationship, called duality T, considers strings that propagate around an additional circular dimension. In 1997, the anti-de Sitter/conformal field theory correspondence (AdS/CFT) was discovered,[15] which links the string theory with a quantum field theory.[16] In a more general framework, AdS/CFT correspondence is a duality that correlates string theory with other physical theories better understood theoretically, with implications in the study of black holes and quantum gravity, but also in nuclear physics[17] and condensed matter.[18]

The dualities in string theory have been linked by philosophers with issues specific to philosophy, such as underdetermination, conventionalism and emergency/reduction. Thus, spacetime has come to be considered by some physicists as an emergent entity, which depends, for example, on the coupling power that governs physical interactions. According to the ADS/CFT duality, a 10-dimensional string theory is observationally equivalent to a 4-dimensional gauge theory - the "gauge/gravity" duality. It follows from these dualities that the theories, being equivalent, are not fundamental, and therefore neither spacetime described is fundamental, but an emergent phenomenon.[19] In this program, gauge theory and gravitational theory are classic limits of a more comprehensive, unifying quantum theory. Philosophers

---

[11] Gregory Moore, “What Is... a Brane?,” *Notices of the American Mathematical Society* 52, no. 2 (November 28, 2005): 214, https://www.researchwithrutgers.com/en/publications/what-is-a-brane.

[12] Becker, Becker, and Schwarz, *String Theory and M-Theory*, 9–12.

[13] Dawid, “Scientific Realism in the Age of String Theory.”

[14] Becker, Becker, and Schwarz, *String Theory and M-Theory*.

[15] Becker, Becker, and Schwarz, 14–15.

[16] Zwiebach, *A First Course in String Theory*, 376.

[17] Igor R. Klebanov and Juan M. Maldacena, “Solving Quantum Field Theories via Curved Spacetimes,” *Physics Today* 62, no. 1 (January 1, 2009): 62 (1): 28–33, https://doi.org/10.1063/1.3074260.

[18] Subir Sachdev, “Strange and Stringy,” *Scientific American* 308 (December 1, 2012): 308 (44): 44–51, https://doi.org/10.1038/scientificamerican0113-44.

[19] Tiziana Vistarini, “Emergent Spacetime in String Theory,” 2013, 103.

question whether two dual theories are physically distinct or only notational variants of the same theory. [20] [21]

In 1995, Edward Witten suggested that the five families of theories in the string theory research program are special limiting cases of an 11-dimensional theory called M-theory. [22] In 1997, Tom Banks, Willy Fischler, Stephen Shenker and Leonard Susskind proposed a matrix model for the 11-dimensional M theory, where the reduced energy limit of this model is eleven-dimensional supergravity. [23]

Feynman regards quantum gravity as "just another quantum field theory" such as quantum electrodynamics. The different types of existing particles are different excitations of the same string. Since one of the modes of string oscillation is a spin-2 massless state that identifies with graviton, string theory necessarily includes quantum gravity. String theory modifies the point gravity of particles at short distances by exchange of massive states of strings. [24] In string theory, the spacetime dimension is not an intrinsic property of the theory itself, but a property of the particular solution.

While string theory cannot currently provide falsifiable predictions, it has, however, inspired new and imaginative proposals for solving outstanding problems in particle physics and cosmology. Early string theory, when dealing with hadron physics, can explain why fermions come in three hierarchical generations, and mixing rates between generations of quarks. [25] In the second period when it approached quantum gravity, the theory addressed the paradox of information about the black hole, [26] counting the correct entropy of the black holes and the processes of changing the topology. [27] The discovery of AdS/CFT correspondence led to a formulation of string theory based on quantum field theory, better understood, and provided a

---

[20] Joseph Polchinski, "Dualities of Fields and Strings," *ArXiv:1412.5704 [Hep-Th]*, December 17, 2014, http://arxiv.org/abs/1412.5704.

[21] Dean Rickles, "A Philosopher Looks at String Dualities," *Studies in the History and Philosophy of Modern Physics* 42 (2011): 42: 54–67, https://doi.org/10.1016/j.shpsb.2010.12.005.

[22] Michael J. Duff, "The Theory Formerly Known as Strings," *Scientific American* 278 (February 1, 1998): 278 (2): 64–9, https://doi.org/10.1038/scientificamerican0298-64.

[23] T. Banks et al., "M Theory as a Matrix Model: A Conjecture," *Physical Review D* 55, no. 8 (April 15, 1997): 55 (8): 5112–5128, https://doi.org/10.1103/PhysRevD.55.5112.

[24] Richard P Feynman et al., *Feynman Lectures on Gravitation* (Reading, Mass.: Addison-Wesley, 1995).

[25] Jonathan J. Heckman and Cumrun Vafa, "Flavor Hierarchy From F-Theory," *Nuclear Physics B* 837, no. 1–2 (September 2010): 837 (1): 137–151, https://doi.org/10.1016/j.nuclphysb.2010.05.009.

[26] Andrew Strominger and Cumrun Vafa, "Microscopic Origin of the Bekenstein-Hawking Entropy," *Physics Letters B* 379, no. 1 (June 27, 1996): 379 (1–4): 99–104, https://doi.org/10.1016/0370-2693(96)00345-0.

[27] A. Adams et al., "Things Fall Apart: Topology Change from Winding Tachyons," *Journal of High Energy Physics* 2005, no. 10 (October 11, 2005): (10): 033, https://doi.org/10.1088/1126-6708/2005/10/033.

general framework for solving black hole paradoxes, [28] such as in Hawkins radiation of black holes (information paradox). [29] Through his research program, he led to many theoretical discoveries in mathematics and gauge theory.

String theory is considered to be a useful tool in investigating the theoretical properties of the thermodynamics of black holes, [30] respectively their entropy. [31] The theoretical basis for these investigations has taken into account the case of idealized black holes, with the smallest possible mass compatible with a given task. [32] This result can be generalized to any theory of gravity, [33] being able to extend to non-extreme astrophysical black holes. [34]

In the Big Bang theory, part of the predominant cosmological model for the universe, the initial rapid expansion of the universe, is caused by a hypothetical particle called inflaton. The exact properties of this particle are not known. They should be derived from a more fundamental theory, such as string theory. [35] The development of this subprogram within the string theory research program is under development. [36]

In brane theory, brane D was identified with black hole supergravitation solutions. Leonard Susskind identified the holographic principle of Gerardus' t Hooft with common states of thermal black holes.

Recently, some experiments in other fields, such as condensed matter physics, have used theoretical results of string theory. [37] And the quantum inseparability in superconductors is largely based on the ideas of duality and additional spatial dimensions developed in string theory. With the help of the duality between 4-dimensional gauge theories and 5-dimensional gravity, string theorists have predicted the experimental value of plasma entropy, a result not

---

[28] Sebastian de Haro et al., "Forty Years of String Theory Reflecting on the Foundations," *Foundations of Physics* 43, no. 1 (January 1, 2013): 2, https://doi.org/10.1007/s10701-012-9691-3.

[29] Leonard Susskind, *The Black Hole War: My Battle with Stephen Hawking to Make the World Safe for Quantum Mechanics*, Reprint edition (New York: Back Bay Books, 2009).

[30] de Haro et al., "Forty Years of String Theory Reflecting on the Foundations," 2.

[31] Yau, *The Shape of Inner Space*, 189.

[32] Yau, 192–93.

[33] Andrew Strominger, "Black Hole Entropy from Near-Horizon Microstates," *Journal of High Energy Physics* 1998, no. 02 (February 15, 1998): (2): 009, https://doi.org/10.1088/1126-6708/1998/02/009.

[34] Alejandra Castro, Alexander Maloney, and Andrew Strominger, "Hidden Conformal Symmetry of the Kerr Black Hole," *Physical Review D* 82, no. 2 (July 13, 2010): (2): 024008, https://doi.org/10.1103/PhysRevD.82.024008.

[35] Becker, Becker, and Schwarz, *String Theory and M-Theory*, 533.

[36] Becker, Becker, and Schwarz, 539–43.

[37] Sachdev, "Strange and Stringy," 44–51.

obtained by any other theoretical model, but these are not absolute experimental validations.[38] [39]

It is hoped that the additional dimensions can be observed with the Hadron Collider (LHC) from CERN, Geneva, but a possible denial would not mean refuting the theory.

For many researchers, gauge theory is considered the only way to renormalize relationships, and string theory is the only option to eliminate the infinities of a unifying program of quantum physics and gravity. The string theory was initially experimentally corroborated as a theory of particle physics, but in the current development it is considered to be far from being falsifiable. The continuation of the program is based on the confidence that theory is the best candidate for a total unifying program. Its credibility is enhanced by the interconnections created during its development, as in the case of supersymmetry and cosmology of black holes.

String theory still does not have a satisfactory definition in all circumstances. The theory uses perturbative techniques,[40] but has not yet clarified the aspects of determining the properties of the universe,[41] so it has attracted criticism from scientists, questioning the value of research in this direction.[42]

Critics of string theory draw attention to the large number of possible solutions described by the string theory. According to Woit,

> "The possible existence of, say, 10^{500} consistent different vacuum states for superstring theory probably destroys the hope of using the theory to predict anything. If one picks among this large set just those states whose properties agree with present experimental observations, it is likely there still will be such a large number of these that one can get just about whatever value one wants for the results of any new observation."[43]

---

[38] Richard Dawid, *String Theory and the Scientific Method*, 1 edition (Cambridge: Cambridge University Press, 2013).

[39] Paul Verhagen, "Understanding the Theory of Everything: Evaluating Criticism Aimed at String Theory" (Amsterdam University College, 2015), http://www.uva.nl/binaries/content/documents/personalpages/h/a/s.deharo/en/tab-three/tab-three/cpitem%5B8%5D/asset.

[40] Becker, Becker, and Schwarz, *String Theory and M-Theory*, 8.

[41] Becker, Becker, and Schwarz, 13–14.

[42] A. Zee, *Quantum Field Theory in a Nutshell, 2nd Edition*, 2 edition (Princeton, N.J: Princeton University Press, 2010).

[43] Peter Woit, *Not Even Wrong: The Failure of String Theory and the Search for Unity in Physical Law*, Reprint edition (Basic Books, 2007), 242.

The supporters of the theory argue that this can be an advantage, allowing a natural anthropic explanation of the observed values of the physical constants. [44]

Another criticism focuses on the dependence of the background theory, as opposed to general relativity. Lee Smolin argues that this is the main weakness of string theory as a theory of quantum gravity. [45]

The solutions of the theory are not unique, and there is no perturbative mechanism to select a particular solution or to choose the true vacuum. Thus, the perturbative formulation of string theory loses its predictive power. Also, there is no perturbative mechanism to select solutions that support low energy spectra that are not supersymmetrical. [46]

Paul Verhagen asks how we should evaluate string theory; can a theory that has considerable difficulties with experimental verification to be classified as a science? to answer this question we must analyze the origins of the different concepts used in theory, evaluate the need for a large unified theory, and focus on evaluating its scientific situation. Some argue that string theory has failed, while others point to its theoretical progress. There is a "meta-paradigmatic rift" between experimentalists and theorists in this regard. [47]

Chalmers believes that a theory must be falsifiable in Popper's sense[48] in order to be scientific: "If a statement is unfalsifiable, then the world can have any properties whatsoever, and can behave in any way whatsoever, without conflicting with the statement." [49] In this sense, string theory is considered as non-falsifiable. [50] The current technology is not precise enough to develop experiments to verify string theory. But the theory is "potentially" falsifiable; makes some predictions, such as the existence of additional dimensions, but they cannot be verified, at least for now. And not yet all the mathematical consequences of the axioms have been elaborated to detect possible conflicts with the observed reality. But efforts are being made in this direction, both for the experimental and the theoretical part.

---

[44] Woit, 242.

[45] Lee Smolin, *The Trouble With Physics: The Rise of String Theory, The Fall of a Science, and What Comes Next*, Reprint edition (Boston u.a: Mariner Books, 2007), 184.

[46] Feynman et al., *Feynman Lectures on Gravitation.*

[47] Verhagen, "Understanding the Theory of Everything: Evaluating Criticism Aimed at String Theory."

[48] Karl Popper, *Conjectures and Refutations: The Growth of Scientific Knowledge*, 2nd edition (London ; New York: Routledge, 2002).

[49] Alan F. Chalmers, *What Is This Thing Called Science?*, 3 edition (Indianapolis: Hackett Publishing Co., 1999), 63.

[50] H. Georgi and Paul Davies, *Grand Unified Theories, in The New Physics* (Cambridge University Press, 1992).

String physicists are accused of ignoring empirical testability and that are replacing this criterion with mathematical arguments. Some of the questions of physicists and philosophers are:

1. Does a theory need to be testable, or are mental experiments sufficient?
2. Does a theory need to make verifiable predictions, or is indirect testability sufficient?
3. A theory without predictions, with only probability distributions, is considered testable?
4. Should the tests be necessarily empirical, or can mathematical consistency checks be considered tests?
5. If contradictory or unacceptable results are obtained from the mental tests by reduction to the absurd, what is the value of these tests?
6. When can testability be requested? Is the possibility of future testing valid?
7. How important is testability in relation to other epistemic desires? Is a theory easy to test but with a low explanatory value preferred over a non-testable theory but with a higher explanatory power? But if the testable theory is too complicated and the non-testable one is simple and elegant?
8. Are predictions of new phenomena more important than pre- or retrodictions of already known phenomena? [51]

Reiner Hedrich suggests[52] that the current failure of string theory could be due to the wrong mathematical device chosen, using the mathematics of the continuum. It is possible that when the theory finds its fundamental principle, it may lead to a more appropriate mathematical basis. An independent background formulation and holographic principle could help heuristic in finding this principle. But it is possible that the principle will never be found, possibly due to the wrong basic assumptions.

Currently, string theory is the dominant research program in the theoretical physics of high energy, [53] considered by some scientists as no viable alternative. [54] Peter Woit regards this status of theory as unhealthy and detrimental to the future of fundamental physics, its popularity largely due to the financial structure of the academic environment and the fierce competition of limited resources. [55] Roger Penrose expresses similar views, saying: "The often frantic competitiveness that this ease of communication engenders leads to bandwagon effects, where researchers fear to be left behind if they do not join in." [56]

---

[51] Helge Kragh, “Fundamental Theories and Epistemic Shifts: Can History of Science Serve as a Guide?,” *ArXiv:1702.05648 [Physics]*, February 18, 2017, http://arxiv.org/abs/1702.05648.

[52] Reiner Hedrich, “The Internal and External Problems of String Theory: A Philosophical View,” *Journal for General Philosophy of Science / Zeitschrift Für Allgemeine Wissenschaftstheorie* 38, no. 2 (2006): 261–278.

[53] Roger Penrose, *The Road to Reality: A Complete Guide to the Laws of the Universe*, Reprint edition (New York: Vintage, 2007), 1017.

[54] Woit, *Not Even Wrong*, chap. 16.

[55] Woit, 239.

[56] Penrose, *The Road to Reality*, 1018.

Logical positivists considered that the scientific method means the deduction of nature models from observations. String theory was initially developed based on an observed fact, the Regge slopes, which at present is no longer considered to be explained by this theory. And the theory has so far not been confirmed by any empirical experiment or observation. But it continued to develop, supported by the belief of many physicists that it is much better than quantum field theory for quantum gravity, and in the hope that it will help unify gravity with other fundamental forces. Most supporters seem to be completely indifferent to experiments and observations, being rather concerned with the "elegance" of mathematical formulation of the theory. [57] For this reason, a reconciliation between string theory and logical positivists seems impossible. [58]

Richard Dawid argues that string theory is based on observations, but its problem would be the huge "theoretical distance" between observable phenomena and scientific concepts. Some researchers argue that the principle of empirical underdetermination of scientific theories does not admit that this "theoretical distance" can be made to allow reliable claims about nature. To this end, Dawid believes that the principle of underdetermination must be replaced by arguments that support string theory. The problem of this theory is, according to Dawid, arbitrariness in choosing its fundamental principles. The theory has a certain set of physical postulates, but there is a continuous erosion of these postulates that follows a uniquely determined linear path. Thus, Dawid asserts that the disagreement between string theorists and phenomenological physicists on string status disappears due to a dramatic change in the characteristics of scientific theory: the old concept of underdetermination of scientific theories in modern particle physics gradually loses ground against the theory of uniqueness. String theory would induce a new understanding of what may be called a scientific statement about nature: the claim of theoretical uniqueness is sufficient for the adoption of a new scientific theory. [59]

In 1995, from the unification of string theories was born the most demanding, unifier gravity research program, the 11-dimensional M-theory, [60] in order to unify gravity with all other fundamental forces in physics.

---

[57] F. David Peat, *Superstrings and the Search for the Theory of Everything*, 1 edition (Place of publication not identified: McGraw-Hill Education, 1989), 276.

[58] Verhagen, "Understanding the Theory of Everything: Evaluating Criticism Aimed at String Theory."

[59] Dawid, "Scientific Realism in the Age of String Theory."

[60] Duff, "The Theory Formerly Known as Strings," 278 (2): 64–9.

Bibliography

Adams, A., X. Liu, J. McGreevy, A. Saltman, and E. Silverstein. "Things Fall Apart: Topology Change from Winding Tachyons." *Journal of High Energy Physics* 2005, no. 10 (October 11, 2005): 033–033. https://doi.org/10.1088/1126-6708/2005/10/033.

Banks, T., W. Fischler, S. H. Shenker, and L. Susskind. "M Theory as a Matrix Model: A Conjecture." *Physical Review D* 55, no. 8 (April 15, 1997): 5112–28. https://doi.org/10.1103/PhysRevD.55.5112.

Becker, Katrin, Melanie Becker, and John H. Schwarz. *String Theory and M-Theory: A Modern Introduction*. Cambridge ; New York: Cambridge University Press, 2007.

Capelli, A. "The Birth of String Theory Edited by Andrea Cappelli." Cambridge Core, April 2012. https://doi.org/10.1017/CBO9780511977725.

Castro, Alejandra, Alexander Maloney, and Andrew Strominger. "Hidden Conformal Symmetry of the Kerr Black Hole." *Physical Review D* 82, no. 2 (July 13, 2010): 024008. https://doi.org/10.1103/PhysRevD.82.024008.

Chalmers, Alan F. *What Is This Thing Called Science?* 3 edition. Indianapolis: Hackett Publishing Co., 1999.

Dawid, Richard. "Scientific Realism in the Age of String Theory." *Physics and Philosophy*, 2007.

———. *String Theory and the Scientific Method*. 1 edition. Cambridge: Cambridge University Press, 2013.

Duff, Michael J. "The Theory Formerly Known as Strings." *Scientific American* 278 (February 1, 1998): 64–69. https://doi.org/10.1038/scientificamerican0298-64.

Feynman, Richard P, Fernando B Morinigo, William G Wagner, and Brian Hatfield. *Feynman Lectures on Gravitation*. Reading, Mass.: Addison-Wesley, 1995.

Georgi, H., and Paul Davies. *Grand Unified Theories, in The New Physics*. Cambridge University Press, 1992.

Haro, Sebastian de, Dennis Dieks, Gerard 't Hooft, and Erik Verlinde. "Forty Years of String Theory Reflecting on the Foundations." *Foundations of Physics* 43, no. 1 (January 1, 2013): 1–7. https://doi.org/10.1007/s10701-012-9691-3.

Heckman, Jonathan J., and Cumrun Vafa. "Flavor Hierarchy From F-Theory." *Nuclear Physics B* 837, no. 1–2 (September 2010): 137–51. https://doi.org/10.1016/j.nuclphysb.2010.05.009.

Hedrich, Reiner. "The Internal and External Problems of String Theory: A Philosophical View." *Journal for General Philosophy of Science / Zeitschrift Für Allgemeine Wissenschaftstheorie* 38, no. 2 (2006): 261–278.

Klebanov, Igor R., and Juan M. Maldacena. "Solving Quantum Field Theories via Curved Spacetimes." *Physics Today* 62, no. 1 (January 1, 2009): 28–33. https://doi.org/10.1063/1.3074260.

Kragh, Helge. "Fundamental Theories and Epistemic Shifts: Can History of Science Serve as a Guide?" *ArXiv:1702.05648 [Physics]*, February 18, 2017. http://arxiv.org/abs/1702.05648.

Lam, Vincent. "Quantum Structure and Spacetime." *Metaphysics in Contemporary Physics*, January 1, 2016, 81–99. https://doi.org/10.1163/9789004310827_005.

Moore, Gregory. "What Is... a Brane?" *Notices of the American Mathematical Society* 52, no. 2 (November 28, 2005): 214–15. https://www.researchwithrutgers.com/en/publications/what-is-a-brane.

Peat, F. David. *Superstrings and the Search for the Theory of Everything*. 1 edition. Place of publication not identified: McGraw-Hill Education, 1989.

Penrose, Roger. *The Road to Reality: A Complete Guide to the Laws of the Universe*. Reprint edition. New York: Vintage, 2007.

Polchinski, Joseph. "Dualities of Fields and Strings." *ArXiv:1412.5704 [Hep-Th]*, December 17, 2014. http://arxiv.org/abs/1412.5704.

Popper, Karl. *Conjectures and Refutations: The Growth of Scientific Knowledge*. 2nd edition. London ; New York: Routledge, 2002.

Randall, Lisa, and Raman Sundrum. “An Alternative to Compactification.” *Physical Review Letters* 83, no. 23 (December 6, 1999): 4690–93. https://doi.org/10.1103/PhysRevLett.83.4690.

Rickles, Dean. “A Philosopher Looks at String Dualities.” *Studies in the History and Philosophy of Modern Physics* 42 (2011): 54–67. https://doi.org/10.1016/j.shpsb.2010.12.005.

Sachdev, Subir. “Strange and Stringy.” *Scientific American* 308 (December 1, 2012): 44–51. https://doi.org/10.1038/scientificamerican0113-44.

Smolin, Lee. *The Trouble With Physics: The Rise of String Theory, The Fall of a Science, and What Comes Next*. Reprint edition. Boston u.a: Mariner Books, 2007.

Strominger, Andrew. “Black Hole Entropy from Near-Horizon Microstates.” *Journal of High Energy Physics* 1998, no. 02 (February 15, 1998): 009–009. https://doi.org/10.1088/1126-6708/1998/02/009.

Strominger, Andrew, and Cumrun Vafa. “Microscopic Origin of the Bekenstein-Hawking Entropy.” *Physics Letters B* 379, no. 1 (June 27, 1996): 99–104. https://doi.org/10.1016/0370-2693(96)00345-0.

Susskind, Leonard. *The Black Hole War: My Battle with Stephen Hawking to Make the World Safe for Quantum Mechanics*. Reprint edition. New York: Back Bay Books, 2009.

Verhagen, Paul. “Understanding the Theory of Everything: Evaluating Criticism Aimed at String Theory.” Amsterdam University College, 2015. http://www.uva.nl/binaries/content/documents/personalpages/h/a/s.deharo/en/tab-three/tab-three/cpitem%5B8%5D/asset.

Vistarini, Tiziana. “Emergent Spacetime in String Theory,” 2013, 103.

Woit, Peter. *Not Even Wrong: The Failure of String Theory and the Search for Unity in Physical Law*. Reprint edition. Basic Books, 2007.

Yau, Shing-Tung. *The Shape of Inner Space*. Reprint edition. Basic Books, 2012.

Zee, A. *Quantum Field Theory in a Nutshell, 2nd Edition*. 2 edition. Princeton, N.J: Princeton University Press, 2010.

Zwiebach, Barton. *A First Course in String Theory*. 2 edition. Cambridge ; New York: Cambridge University Press, 2009.