

Section Three

COSMOS AND HISTORY

Does a Theory of Everything Exist?

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Since Einstein's failure to define a Grand Unified Theory, physicists have pursued a comprehensive theory explaining nature, a Theory of Everything. But because General Relativity, Quantum Field Theory, and Cosmology have little in common, defining one theory is an imposing task, having eluded the best scientists for ninety years. So are we close to defining a Theory of Everything? This analysis, after defining requirements (which must include initial conditions), identifies four possible options for a Theory of Everything. Quotes from prominent physicists express divergent views on each alternative.

The leading proposal for a Theory of Everything is String Theory, which has possible issues. It requires supersymmetry, has extra compacted dimensions, and is background-dependent. A second less comprehensive theory is Loop Quantum Gravity, which emphasizes background-independence based on discrete quantum space. Explaining how theories define relationships between spacetime, quantum space, quantum time, and quantum gravity, positions the role of background-independence in proposed theories.

If supersymmetry and extra dimensions are discovered, String Theory or a modified String Theory integrated with Loop Quantum Gravity, may be the option. Or, possibly a radically new theory might be developed. Or, as the last option considers, the answer to the question — Does a Theory of Everything exist? — may be no; if so, nature will always be a mystery.

Keywords: theory of everything, string theory, loop quantum gravity, general relativity, quantum mechanics, cosmology, spacetime

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Introduction

Scientists labored two thousand years before clarifying how the world acts according to classical mechanics (1800's). Subsequently, another hundred years transpired before Einstein discovered general relativity and another decade transpired before the micro-world of quantum mechanics was defined in 1926. With the detection of the cosmic microwave background in 1967, cosmology flourished. After quantum chromodynamics was defined in the early 1970s, particle and force interactions were predicted to extreme precision. These successes are well known, but there remained one big task, a task Einstein failed (although he labored over it from 1915 until his death) — how to integrate general relativity and electromagnetism into a Grand Unified Theory (GUT). Subsequently, in the 1970s, quantum field theory described all three non-gravitational forces in the same mathematical language. Thus, to obtain a complete description of nature, only gravity was excluded. However, calculations involving quantum mechanics and general relativity produced Illogical results.

We now refer to this big task, the ultimate goal of physics, as defining a Theory of Everything (TOE) — a theory encompassing relativity, cosmology, and quantum mechanics. But why is a TOE needed? Is there a fundamental reason that a TOE exists? Quoting Brian Greene, “Because the gravitational field is woven within the very fabric of spacetime, its quantum jitters shake the entire structure through and through. When used to analyze such pervasive quantum jitters, the mathematical methods collapsed. For years, physics turned a blind eye to this problem because it surfaces only under the most extreme conditions ... when gravity and quantum mechanics are together brought to bear on either the big bang or black hole, realms that *do* involve extremes of enormous mass squeezed to a small size, the math falls apart at a critical point in the analysis” (Greene, 2011: 77-78). Greene continues, “It is hard to believe that the deepest understanding of the universe consists of an uneasy union between two powerful theoretical frameworks that are mutually incompatible. ... We have one universe and therefore, many strongly believe, we should have one theory” (Greene, 2004: 336).

Based on progress over decades, some scientists are optimistic a TOE will be discovered, others are not. Diverse opinions address each of the four options: String Theory, String Theory combined with Loop Quantum Gravity, a New Theory, and a Theory does not exist.

Perspective

The leading contender for a Theory of Everything (TOE) is Superstring Theory (ST) (Note these acronyms, plus QM for Quantum Field Theory and LQG for Loop Quantum Gravity, will be used in most of the text). But not all physicists support ST because it requires both extra dimensions and supersymmetry, which have not been experimentally verified. Also, being based on the concept of spacetime defined by relativity, ST is background-dependent, a potential problem. Thus, a broad perspective of options for a TOE must include all possibilities as shown in Figure 1,

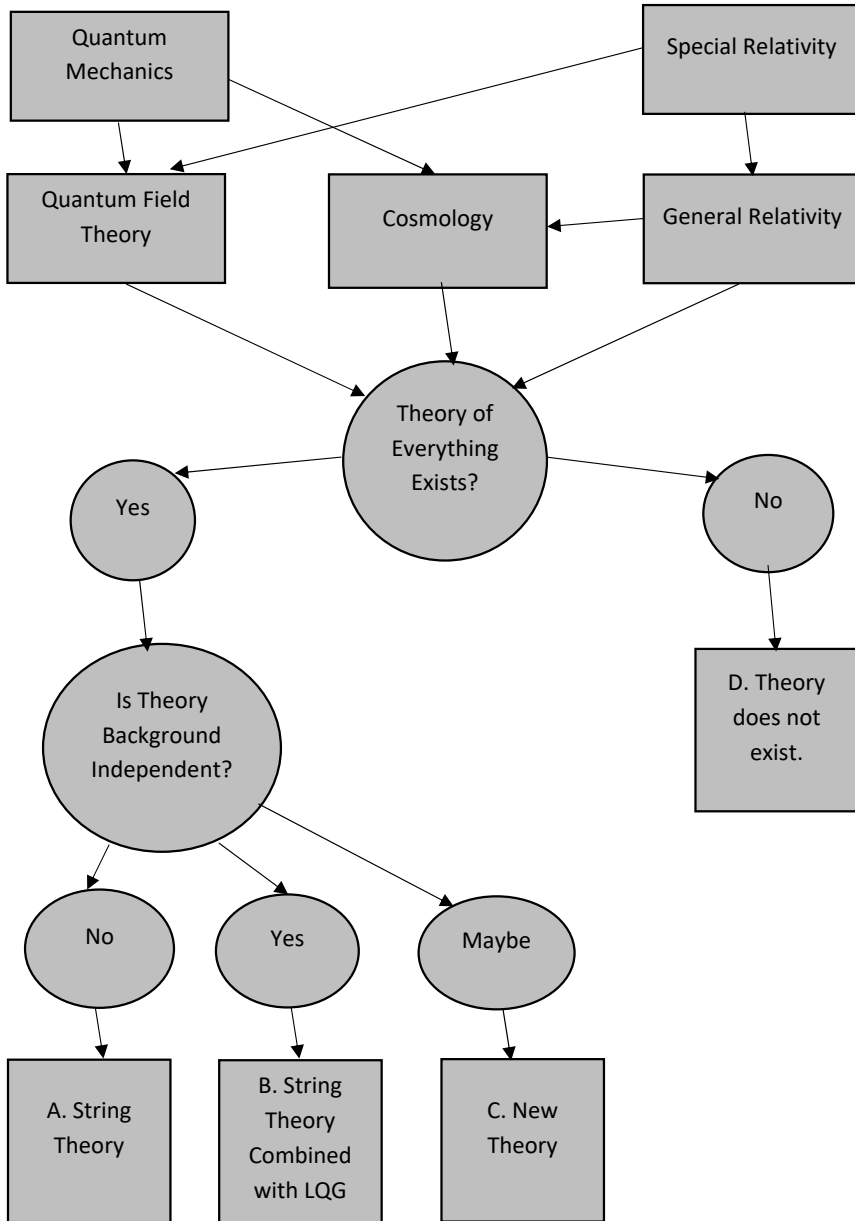


Figure 1. Four Options for Theory of Everything

The top section of the chart depicts the general relationship of a TOE with five major theories (Quantum Mechanics, Quantum Field Theory, Special Relativity, General Relativity, and Cosmology). Conceptually, all the existing fundamental theories could be derived from a TOE. The lower half shows the four possible options: String Theory; String Theory integrated with Loop Quantum Gravity; a completely new theory; and a TOE does not exist. As shown in Figure 1, background-independence is a key issue separating the options.

Requirements

Table 1 lists the general requirements for a TOE (defined by the author). It must: (1) define gravity as quantum, (2) combine the equations of GR and QM to resolve extreme situations and other issues, and (3) explain the values of constants in the Standard Model of Particle Physics (SMPP). By including Cosmology, the study of the origin, evolution, and eventual fate of the universe, as a separate theory, we highlight two additional requirements: (4) explain the constants in the Standard Model of Cosmology (SMC) and (5) explain initial conditions, how energy came into existence, for example via inflation or a cyclic/bounce process. The last requirement (6) is to allow experimental verification. Thus, a TOE must provide solutions to these six requirements. Optional requirements are discussed in the next section. Obviously, since scientists have been working over ninety years on a TOE (previously a unified theory), there are serious issues to overcome. A discussion of each requirement follows.

Define gravity as quantum. The theory of GR is non-quantum, with gravity as an integral property of spacetime. Space and time are interrelated, continuous, and *not quantum* (in the quantum world, energy and mass are quantized using Plank’s constant). Gravity corresponds to spacetime curvature, not a force field, although it acts like one. A TOE defining gravity as a quantum force, like the three other forces of nature, must use spacetime as a backdrop (as in ST) or redefine spacetime (as in LQG).

Requirements for TOE
1. Define gravity as a quantum
2. Combine GR and QM — Quantum Gravity
a) one conceptual approach for forces/particles
b) resolve singularities
3. Explain the values of SMPP constants
a) charge of particles
b) mass of particles
c) force strengths
d) fine structure constant (α)
e) mass electron/mass proton (β)
f) dark matter
4. Explain values of SMC constants
a) density ratios
b) number of photons/baryons
c) homogeneity (Q)
d) dark energy
5. Explain Initial Conditions, cosmology
a) energy source
b) low entropy
c) high pressure and density (temperature)
6. Experimental verification

Table 1. Requirements for TOE

Combining QM and GR. What are the differences between GR and QM that need resolution? The crux of the problem is summarized by Eugene Wigner, “Quantum mechanics and general relativity operate in different math concepts: four dimensional Riemann space and infinite dimensional Hilbert space” (Wigner, 1960). In addition to dimensions, there are other inherent differences between GR and QM. As the quote in the introduction from Brian Greene clearly states, combined equations produce erroneous results in extreme situations, a problem for physicists. “The melding of quantum mechanics and general relativity is an ongoing topic of advanced research” (Greene, 2020: 348).

Explain values of the Standard Model of Particle Physics (SMPP) constants. The dimensional values for an electron’s electromagnetic charge, the strengths of forces, and the mass of fundamental particles are determined experimentally. The three SMPP forces — electromagnetic, weak, and strong operate over distance in totally dissimilar ways and vary significantly in relative strength.

For fundamental particle masses, numerous mathematical analyses have been performed. However, plotting the masses of nine fundamental particles (electron, muon, tauon, and six quarks) produces a statistically random distribution rather than a logical pattern (Tegmark, 2014: 146). The logic to predict their values still eludes physicists.

The SMPP has few natural dimensionless constants; most are ratios; the two most useful and most mysterious ratios are the fine structure constant (α) with a value of 0.00729 and the ratio of the electron to proton mass (β) with a value of 0.000545. A TOE should predict correct values for all of these known constants and ratios.

As far as dark matter, theory and astronomical observation allow estimates of its mass, but physicists cannot explain what it is. Thus, a TOE explanation is welcome.

Optional Requirements for TOE

1. All forces converge to a single force at high temperature and short distances (SUSY)
2. Unify particles and forces (SUSY)
3. Extra dimensions (ST)
4. Explain QM mystery (wave collapse)
5. Background-independence
 - a) Space as defined by LQG (spinfoam)
 - b) Space from fundamental entities
 - c) Space “is what it is”

Table 2. Option Requirements for TOE

Explain values of the Standard Model of Cosmology (SMC) constants. “The SMC constants address aspects of space and have virtually nothing in common, and are not derived from, the SMPP constants” (Scott, 2006). The SMC *dimensional* constants are: energy densities (critical, baryon, dark matter, and dark energy) and a number of photons and baryons. “All except the dark energy density actually vary over time but are considered constants because they change so slowly” (Johnson, 2015). And for the last SMC constant, a clear definition of dark energy (cosmological constant) is a necessary requirement.

“The SMC also has a few *dimensionless* constants, primarily the ratios of the dimensional

constants; however, one well-known dimensionless constant is the measure of homogeneity in the universe, denoted by “Q.” It dictates how galaxies and clusters of galaxies form and is actually a ratio — the energy required to disperse cosmic structures (stars, galaxies, and clusters of galaxies) divided by their rest-mass energy” (Johnson, 2015). Q is validated by the difference in the CMB radiation intensity, about two in 100,000 (Tegmark et al., 2006). A TOE should predict this value.

Establish initial conditions (Cosmology). Initially, the big bang requires an energy source (initial conditions), — something to breathe fire into equations and propel the expansion of space itself. Energy density, low entropy, and temperature were established by initial conditions. Various theories (Inflation the predominant one) propose how initial conditions were established. However, a TOE must rely on existing theories or an alternative proposal based on unique assumptions. For example, a theory must propose a source for energy as the inflaton field in the inflation theory or colliding branes in M-Theory. Five proposed theories are briefly described in the Cosmology Insert.

Experimental verification. Experimental verification is a tough requirement because of the minute scale involved, the Planck length (10^{-33} cm) in current theories (both ST and LQG). However, if a theory cannot be experimentally validated, do we have a legitimate theory? It may be that circumstantial evidence is the only possible validation. For example, current tests for ST involve: searching for supersymmetric particles and for evidence of extra dimensions at the Large Hadron Collider; measuring the gravitational strength at small distances to prove that gravity escapes to another dimension; and searching the sky for fine temperature variations in the cosmos background radiation. However, these tests are not conclusive, quoting Brian Greene on tests for ST, “As of today, then, the most promising positive experimental results would most likely not be able to definitely prove string theory right, while negative results would most likely not be able to prove string theory wrong. Yet make no mistake. If we find evidence of extra dimensions, supersymmetry, mini black holes, or any of the other potential signatures, that will be a huge moment in the search for a unified theory”(Greene, 2011: 96).

Will future technology provide more stringent tests that are able to prove a theoretical TOE? Only time may dictate the resolution of this demanding requirement.

Optional Requirements for TOE

A TOE may or may not include the optional TOE requirements listed in Table 2. As an overview, the first three results from supersymmetry and are certainly possible, maybe probable. The fourth, explaining the mysteries of QM, is less probable. The last optional requirement is background-independence. Brief comments on the five requirements are provided next.

The first optional requirement, all forces (including gravity) converge to a single force at high temperature and short distances result from employing supersymmetry: “At the level of coupling strengths, then, we achieve a complete unification among all four basic forces” (Wilczek, 2015: 317). The unification of particles and forces, which allows substance particles to change into force particles and vice versa, is a direct result of supersymmetry. Unification and extra dimensions are both discussed later under option “A.” Explaining the mysteries of QM, specifically how waves collapse and non-locality, is more a question of philosophy; thus, a TOE may not explain “everything.”

The last optional requirement is background-independence, which in our context, means a theory where space and time emerge from more fundamental entities; thus, space and time

would be functions dependent on other variables defined within the theory. Alternatives for background-independence are: (a) space defined by spinfoam in LQG or (b) spacetime emerging from other unknown entities. A theory could also be valid if it does not meet this definition of background-independence because it is conceivable that spacetime is *fundamental* and may not exhibit a quantum nature or be constructed from more fundamental quantum entities. In other words, spacetime “is what it is.” Thus, background-independence is considered an optional requirement.

We can consider the spacetime background possibilities for gravity by asking a question: Is gravity a property of spacetime as defined by GR? If the answer is yes, spacetime “is what it is” and the gravitational force is *not quantum*. If the answer is no, three possibilities will be explored: LQG, ST with LQG, and a completely new theory. Additional specifics on quantum gravity and spacetime are discussed within options and later summarized (Table 3).

TOE Requirements	String Theory/ M-Theory	Loop Quantum Gravity (LQG)
1. Define gravity as a quantum	Yes	Yes
2. Combine QM and GR	Yes	No
3. Explain value of SMPP constants	No, but possibly in future based on Calbi-Yau shape	No, multiverse is explanation
4. Explain value of SMC constants	No, multiverse is explanation	No, multiverse is explanation
5. Cosmology proposal	Yes, Landscape. Brane, Cyclic, Holographic	Yes, Big Bounce
6. Experimental verification	No	No
Optional TOE Requirements		
1. Forces converge to single force (SUSY)	Yes	No
2. Unification of forces and particles (SUSY)	Yes	No, quantum gravity is focus
3. Extra dimensions	Yes	No
4. Explain QM mystery	No	No
5. Background independent?	No, theory based on spacetime as defined by relativity	Yes, establishing background – independence is basis of theory
Additional Comments		
Concept	Vibrating strings for particles and forces	Quantum of space forming spinfoam
Number of dimensions	Ten space with seven compacted and one time dimension	Three space dimensions

Supersymmetry?	Yes	No
New fundamental constants	Yes, two	No
Time fundamental	Yes	No, change based on causality
Mathematics complexity	Very complex, inventing new math in algebraic geometry and topology	Traditional math
Key Dates	1968 (strong force), 1984 (anomalies), 1995 (M-Theory)	1986
Notable Proponents	Brian Greene, Michael Green, Joseph Conlon, Gordan Kane	Carle Rovelli, Lee Smolin, Martin Bojowald

Table 3. Overview of String Theory and Loop Quantum Gravity

Cosmology Insert. Overview of theories referenced
in options A and B

The **Landscape** multiverse combines string theory and eternal inflation (the eternal or chaotic inflation theory produces separate universes, sometimes referred to as bubbles, each separated by expanding space) to predict an infinite number of universes. The significant difference from the Inflationary proposal is that space consists of nine space dimensions instead of the three space dimensions. These extra dimensions provide numerous “shapes” for space, each shape a different variety of the universe.

The **Brane** multiverse evolves from M-theory theory, which has ten space dimensions. The theory predicts multi-dimensional branes. A “one” brane corresponds to a one-dimensional string and a “three” brane corresponds to a three-dimensional space. Thus, our universe could exist on a 3-brane (one of many) with a large or infinite extent. Different branes reside in different dimensions, not necessarily separated by vast distances in space, and possibly hovering in close proximity to each other. All strings are attached to the brane except for gravitons, which are unattached loops that can leave and re-enter the 3-brane (Greene 2011: 118).

The **Cyclic** multiverse is another prediction based on M-theory. In a process that repeats over time, two colliding branes generate new universes. Although laws remain unchanged, the constants of nature may vary as the process repeats. Consequently, there is an explanation for fine-tuning. Some theorists predict periodic collisions between braneworlds that produce Big Bang scenarios. The proposed cycle, occurring over a trillion years, is: collision, expansion, cooling, dispersion and then another collision. Although collisions occur in long cycles, infinite time generates an infinite number of universes that repeat in time. The process excludes a dramatic “inflation” type of expansion.

The **Holographic** multiverse represents two physically equivalent universes, one existing on a two-dimensional boundary surface mirroring a second universe in three-dimensional space. From black-hole theories, physicists conclude that the amount of information contained within a region of space is always less than the area of the surface that surrounds the region (expressed in square Planck units), a strange relationship since volume increases with the cube of a sphere’s radius. Consequently, since all physical phenomena can be encoded on the surrounding surface, our three-dimensional reality could be a holographic projection from a

two-dimensional surface — the holographic principle. Brian Greene views this development as among the most exciting in decades: “A particular *non-gravitational, point particle* quantum field theory in *four* spacetime dimensions describes the same physics as *strings, including gravity*, moving through a particular swath of *ten* spacetime dimensions” (Greene, 2011: 266).

In the **Bounce** multiverse theory, expansion is created from the rebound of a contracting universe (an alternative to inflation). Loop quantum gravity suggests that the atomic structure of spacetime *changes the nature of gravity* at very high energy densities. Loop-based scenarios are founded on general principles of quantum theory and relativity theory and therefore avoid introducing new ad hoc assumptions (as with inflation). When a preexisting universe collapses under the attractive force of gravity, the density grows so high that gravity switches to repulsive and the universe starts expanding again. It bounces (Bojowald, 2008). In this scenario, energy is recycled from the previous universe.

Option A. String Theory

Many physicists believe ST is the answer. In ST, tiny strings of vibrating filaments replace electrons and quarks as nature’s building blocks. Strings are so minute they may never be observed (size on the order of Planck distance of 10^{-33} cm). The string vibration pattern dictates intrinsic features that may represent an electron or a quark or, more importantly, a graviton (massless, chargeless, and having a spin-2 quantum property). Thus, without contradicting previous theories, ST bridges the gap between general relativity and QM. However, the mathematics, as defined in five unique theories, requires nine (ten for M-Theory) rather than three space dimensions. The extra dimensions are curled up into Calabi-Yau shapes, shapes that dictate particle properties. Supersymmetry, which unifies particles and forces, is an optional TOE requirement required for ST.

Why string theory? Theoretically, ST meets three of the six requirements as shown in Table 1: includes quantum gravity, combines QM and GR, and provides four possible cosmological theories addressing initial conditions: Landscape, Brane, Cyclic, and Holographic. For a description of these theories, reference the *Cosmology Insert* that summarizes the descriptions in Brian Greene’s book, *The Hidden Reality* (Greene, 2011: 309).

The three requirements not met, explaining the values of constants for SMPP/SMC and experimental verification, are challenges. Although in principle, ST allows all particle properties to be determined, for example, the same Calabi-Yau shapes yield just the right number of particles, but the calculating mass is more difficult (Greene, 2004: 374). No one has accomplished this. However, as emphasized, ST is still very much a work in progress. Finding the correct shape for existing particles and subsequently, their mass is an active area of research.

	Special	General	String		String Th.	New
Attribute	Relativity	Relativity	Theory	LQG	plus LQG	Theory
Spacetime	Yes ¹	Yes ²	Yes ³	No	No	Maybe ⁷
Space quantum	No	No	Future ⁴	Yes	Yes	Maybe ⁷
Time quantum	No	No	Future ⁴	N/A ⁵	Yes ⁶	Maybe ⁷
Gravity quantum	No	No	Yes	Yes	Yes	Maybe ⁷

Notes.

1. Spacetime is as defined by SR — space and time are interrelated, continuous (not discrete), and not quantum.
2. In the non-quantum theory of GR, gravity is an integral property of spacetime. Gravity corresponds to spacetime curvature, not a force field, although it acts like one.
3. In ST, gravity is quantum. Spacetime is as defined in SR with gravitons (gravity is a separate quantum force field). Thus, string theory is background-dependent on SR.
4. Spacetime emerges from more fundamental entities (based on zero branes, Matrix, or possibly other spaceless timeless entities), and therefore string theory would transition to background-independent.
5. Time not a basic variable in equations, replaced with causal relationships.
6. Assumes the time variable is required in theory.
7. Although a new theory might be based on theoretical spaceless timeless entities, spacetime and gravity could also be as defined by GR (non-quantum).

Table 4. Background-independence attributes and theories

A more generic reason for supporting ST is described by Michael Green (paraphrasing). As time goes by and ST evolves, it is more and more apparent that it is not just a “Theory of string-like elementary particles,” but it is a ‘Magnificent theoretical framework’ that interrelates a wide range of topics in physics and mathematics (Conlon, 2016: 103).

Another way to explain the value of SMPP and SMC constants is an initial condition theory which predicts a multiverse. With this solution, all possibilities exist. Thus, we happen to be living in one which has the “right” constant values to enable life. If the values of constants were slightly different, we would not be around to observe the universe (anthropic principle). ST includes various multiverse options as described in the Cosmology Insert.

Why not ST? As noted in Table 3, Overview of String Theory and Loop Quantum Gravity, ST is background-dependent, has ten space dimensions and requires supersymmetry. Addressing background-independence, Brian Greene says, “No one has yet come up with a spaceless and timeless formulation of string theory — something that physicists call background-independent formulation. Instead, virtually all approaches envision strings as moving and vibrating through a spacetime that is inserted into the theory “by hand”; spacetime does not emerge from the theory Many consider this to be the greatest unsolved problem facing ST” (Greene, 2004: 487). Lee Smolin agrees, “The general theory of relativity is a background-independent theory. A quantum theory of gravity should also be background independent. This means that the whole geometry of space and time should arise from it, not serve as the backdrop for the actions of strings” (Smolin, 2006: 184).

Brian Greene again addresses this issue, “If string theory is correct, the usual concepts of space and time ... simply do not apply on scales finer than the Planck scale — the scale of

strings themselves” (Greene, 2004: 350). There would be no such thing as a distance shorter than the Planck length or a duration shorter than the Planck time. Greene continues, “Another possibility is that space and time do not abruptly cease to have meaning on extremely small scales, but instead gradually morph into other more fundamental concepts. ... Many string theorists, including me, strongly suspect that something along these lines actually happens, but to go further, we need to figure out the more fundamental concepts into which space and time transform” (Greene, 2004: 351).

There are two speculative ST proposals for more elementary constituents: strings-as-threads-of-spacetime; and, Matrix theory, where space and time are formed from zero-branes (Greene, 2004: 488). It is conceivable, however, that spacetime as defined by relativity “is what it is.” More fundamental entities would not be required and background-independence would not be an issue for ST as a TOE.

The concept of having more than three space dimensions was first introduced in 1919 by Kaluza-Klein. The theory *assumed* one extra dimension. “[Fifty] years later, along came string theory. Rather than allowing for a universe with more than three dimensions, the mathematics of string theory *required* it” (Greene, 2011: 88). “*This is a fundamentally different kind of result, one never before encountered in the history of physics. Prior to strings, no theory said anything at all about the number of spatial dimensions in the universe*” (Greene, 2004: 367). The compacted extra dimensions, if discovered, would establish credibility for the theory. To date, experiments have not indicated the existence of extra dimensions.

Supersymmetry is required by ST. It predicts additional particles and thus unifies forces and particles. As Frank Wilczek states, “Supersymmetry is the claim that our world has quantum dimensions and that transformations exist ... which change substance particles into force particles, and vice versa ... Both are the same thing seen from different perspectives” (Wilczek, 2015: 317). “If ... force and substance are the same ... we will have achieved a new level of unity and coherence in our fundamental understanding of nature” (Wilczek, 2015: 390). Representing the other position, Lee Smolin, a noted critic of ST, states, “If the new dimensions and supersymmetry do not exist, then we will count string theorists among science’s greatest failures” (Smolin, 2006: xvii). “If the world turns out to be eleven-dimensional and supersymmetric, I will be the first to applaud their triumph. But for the present ... I no longer believe this is likely” (Smolin, 2006: 373).

Continuing to focus on the why not ST question, a generic argument is proposed by Brian Greene, “But most researchers feel that our current formulation of string theory still lacks the kind of core principle we find at the heart of other major advances. Special Relativity has the consistency of the speed of light. General relativity has the equivalence principle. Quantum mechanics has the uncertainty principle. String theorists continue to grope for an analogous principle that would capture the theory’s essence as completely” (Greene, 2004: 376).

Others, by asking if we have gone too far with mathematics, express a more negative view: “After piling layer on layer of abstract mathematics, theoreticians managed to get string theory working” (Clegg, 2016: 236). And in a similar vein, “The mathematics used in these studies [ST] is becoming more and more advanced. Not only are ordinary numbers replaced by an extended class of numbers known as Grassmann numbers [they satisfy a different multiplication law, $xy = -yx$] ..., ordinary geometry is also superseded by a special branch known as noncommutative geometry” (Livio, 2005: 231). In addition, ST uses abstract math, such as Lie groups and knot theory (Livio, 2009: 203-217). However, most physicists think advanced mathematics is a positive argument supporting ST, not a disadvantage.

Option B. String Theory and LQG

By analyzing Table 3, Overview of String Theory and Loop Quantum Gravity, it is obvious that ST and LQG are not comparable theories. LQG does not address four of the six TOE requirements. Rather it specifically addresses quantum gravity from a background-independent point of view. Consider the following quotes from a LQG expert, Carlo Rovelli, which verify this statement:

1. “Again, loop gravity does not pretend to provide a unified picture of nature, to tell us what the matter content of the universe is, or to determine the number of dimensions of spacetime.” (Rovelli, 2011: 4)
2. “The unification of forces and the quantization of gravity are two conceptually distinct problems. ... Solving the second does not necessarily imply solving the first” (Rovelli, 2011: 5).
3. “The problems addressed by strings and loops do not coincide. ST addresses questions outside the scope of loop gravity, such as: ... what is the final theory of nature?” (Rovelli, 2011: 2).

So what is the principle behind LQG? Rovelli captures the intent as follows. Spacetime is a manifestation of a physical field. All fields we know exhibit quantum properties at some scale. We believe space and time to have quantum properties as well. We must thus modify our understanding of the nature of space and time, in order to take these quantum properties into account. ... We have to understand what quantum space and what quantum time are. This is the difficult side of quantum gravity, but also the source of its beauty” (Rovelli & Vidotto, 2015: 6). “In my opinion, the theory provides an intriguing possible formalism for describing quantum spacetime. It makes predictions at the Planck scale, dealing with the early universe, and offering a coherent conceptual framework where GR and QM cohabit amicably” (Rovelli, 2012: 20).

A conceptual definition of LQG follows: “The relation of special adjacency tie the grains of space into webs called “spin networks.” A Ring in the spin network is a “loop.” The webs in turn, transform into each other in discrete leaps as structures called “spinfoam.” This is the world described by LQG” (Rovelli, 2018: 126). This may sound strange but remember these structures are the spacetime ingredients.

A few important points about LQG (reference Table 3): it is derived based on three space dimensions, does not include supersymmetry, defines discrete space, replaces the time variable with causality, uses traditional math, and includes a cosmology theory, named the big bounce (reference the Cosmology Insert for brief description). As Carlo Rovelli states, “Loop cosmology is the most spectacular success of LQG. The theory elegantly resolves the big bang singularity and predicts a sort of “bounce” from a previous contracting phase” (Rovelli, 2011: 5). Since an infinite number of bounces may occur, LQG is classified as a multiverse providing a solution for the SMPP and SMC constant values (requirements two and three).

Under additional comment in Table 3, there is the question of time in the two theories, with it playing a fundamental role in ST but replaced by causality in LQG. How does causality replace time? Is *time* inherent, or is there a more correct way to explain the change, for example, defining how things change in relation with one another? Quoting Rovelli, “The fundamental equations of quantum gravity do not have a time variable, and they describe the world by indicating the possible relations between variable quantities” (Rovelli, 2018: 119). For justification, he says, “The Heisenberg and Schrödinger pictures are equivalent if there is a normal time evolution in the history. In the absence of a normal notion of time, the

Heisenberg picture remains viable, the Schrödinger picture becomes meaningless. In quantum gravity, only the Heisenberg picture makes sense” (Rovelli, 1999: 12). Further clarifying the role of time, Carlo Rovelli says, “Einstein’s General relativity does not describe evolution in time: it describes the relative evolution of many variables with respect to each other” (Rovelli, 1999: 12); “In quantum gravity, I see no reason to expect a fundamental notion of time to play any role. ... We should simply forget time” (Rovelli, 1999: 13). Even with this explanation, equations without time are non-intuitive to most people.

Is it possible that ST and LQG are complementary theories and create a valid option? Brian Greene provides his opinion, “If I had to hazard a guess on future developments, I’d imagine that the background-independent techniques developed by the LQG community will be adapted to string theory, paving the way for a string formulation that is background-independent. And that’s the spark that will ignite a third superstring revolution in which, I’m optimistic, many of the remaining deep mysteries will be solved” (Greene, 2004: 491).

In a less optimistic opinion, Carlo Rovelli says, “If there is a fundamental description of strings, this should be background-independent, perhaps could it resemble somehow LQG?... Would it lead toward something more resembling strings? If I had to bet, I would say no, the two paths are really different, but I would not rule out the possibility a priori” (Motl & Rovelli, 2011). In a completely negative opinion, string theorist Lubos Motl says, “An equivalence between LQG and ST — or an LQG-like description of strings in physics — has surely been an attractive idea for many physicists (myself included) but it is impossible because of fundamental differences in virtually all general features and predictions of both frameworks” (Motl & Rovelli, 2011).

Option C. New Theory

As previously discussed, there are good reasons why GR and QM are incompatible. One way to resolve the contradiction between the two theories is to assume that both theories are approximations of another yet unknown theory. A new theory must satisfy the TOE requirements but could also include a series of “maybe” assumptions, for example: maybe background-independent; maybe supersymmetry; maybe an explanation of QM; maybe both discrete and continuous entities; maybe more fundamental entities of space and time; and, maybe new sophisticated mathematics. A few noted physicists have considered the possibility that ST and LQG are not the answer for a TOE:

1. “Composite spacetime would mean that an even more elemental description of the universe — one that is spaceless and timeless — has yet to be discovered” (Greene, 2004: 472).
2. “So what is everything ultimately made of? ... We simply don’t know yet, but there is good reason to suspect that everything we know of so far — including the fabric of spacetime itself — is ultimately made up of some more fundamental building blocks” (Tegmark, 2014: 163).
3. “On the other hand, I think that the theory [LQG] is still fragmented, and I am far from sure that it is physically correct or that it has already reached its definite form. ... And even if the theory was fully coherent, of course, nature could have chosen something else” (Rovelli, 2012: 20).
4. “Clearly if string theory or LQG by themselves were an answer, we would know it by now. They may be starting points, they may be parts of the answer, and they may contain necessary lessons. But the right theory must contain new elements...” (Smolin, 2006: 258).

It might be improbable, but if we assume experimental evidence contradicts one or more of the predictions or premises of ST (strings, extra dimensions, and supersymmetry) and LQG (spacetime emergence), physicists must return to the drawing board and develop a new approach for a TOE.

In addition to meeting the TOE requirements, one key conceptual issue a new theory must address is background-independence (optional requirement five) — are space and time emergent as in LQG, or is spacetime fundamental as in GR?

What role would time play in a new theory? Time seems as fundamental as anything in the world. For example, the theory of GR treats time as a dynamic variable that interacts directly with matter/energy. But when discussing LQG, Carl Rovelli argued that we should forget time. Thus, is there a more correct way to explain the change, for example, by defining how things change in relation with one another? Are relationships among entities more fundamental than time relationships? Brian Greene joins the debate when he explains attempts to merge GR and QM, “In the central equation that emerges, it turns out that the time variable does not occur. So rather than having an explicit mathematical embodiment of time — as in the case of every other fundamental theory — in this approach to quantizing gravity, temporal evolution must be kept track of by a physical feature of the universe (such as density) that we expect to change in a regular manner. ... it is not clear whether the absence of an explicit time variable is hinting at something deep (time as an emergent concept) or not” (Greene, 2004: 527).

Earlier, when discussing background-dependence for ST, it was described as a “potential” weakness because even though the majority of physicists think it is a problem, *it might not be a problem*. Spacetime may be just spacetime, with no additional fundamental spaceless and timeless entities. However, offsetting this view are Brian Greene’s comments on spacetime, “Is spacetime a something, or isn’t it? ... I believe that an experimentally confirmed, background-independent union between general relativity and quantum mechanics would yield a gratifying solution to this issue. ... Then, the theory’s ingredients — be they strings, branes, loops, or something else discovered in the course of further research — coalesced to produce a familiar, large-scale spacetime” (Greene, 2004: 491).

Another conceptually new theory different from both ST and LQG is proposed by Sean Carroll in his book, *Something Deeply Hidden*. He bases the theory on the Schrodinger equation, “String theory, loop quantum gravity, and other ideas share a common pattern: they start with a set of classical variables, then quantize. From the perspective we’ve been following in this book, that’s a little backward. Nature is quantum from the start. Described by a wave function evolving according to an appropriate version of the Schrodinger equation. Things like “space” and “fields” and “particles” are useful ways of talking about what way functions in an appropriate classical limit. We don’t want to start with space and fields and quantize them: we want to extract them from an intrinsically quantum wave function” (Carroll, 2019: 275).

Relating background-independence to fundamental theories and our first three TOE options, can be confusing since it involves space, time, spacetime, and quantum gravity. Table 4, Background-independence Attributes and Theories, summarizes the alternatives we have discussed.

Option D. No TOE Solution, always a mystery

The science world in the 1920s thought that there was nothing new to discover, but they were shocked by QM and a host of observational discoveries in cosmology. A TOE

is an elusive, problematic topic and ST, as the primary theory proposed, is a promising but unverified theory. If it were to fail, the options are a new theory or a theory does not exist. We may have reached a time where significant advances in theory development are over.

It is conceivable a new branch of mathematics might help define a new theory, but the prospect of this is unknown. Although ST has advanced fields of mathematics in the areas of topology and algebraic geometry, other advances are not guaranteed.

Returning to experimental verification, which supports a No Solution option, Greene says, “Until our theories make contact with observable, testable phenomena, they remain in limbo — they remain a promising collection of ideas that may or may not have relevance for the real world” (Greene, 2004: 493).

Addressing the question of No Solution option based on previous research regarding ST, Lee Smolin says, “It is not an exaggeration to say that hundreds of careers and hundreds of millions of dollars have been spent in the last thirty years in search for signs of grand unification, supersymmetry, and higher dimensions. Despite these efforts, no evidence for any of these hypotheses has turned up” (Smolin, 2006: 176), and, “If a large number of people have worked on a question for many years and the answer remains unknown, it may mean that the answer is not easy or obvious. Or this may be a question that has no answer” (Smolin, 2006: xvii). Nature may want to retain its true identity as a mystery.

Summary

In this survey article, after ascertaining TOE requirements and options, divergent opinions on a number of controversial issues were quoted from noted experts in the fields of ST, LQG, and cosmology. Topics covered were: credibility of ST; possibility of merging ST and LQG; background-independence; replacing the time variable with causality; fundamental timeless, spaceless entities; initial conditions; circumstantial experimental verification; a new theory option; and the possible option of no solution.

Because of physicists’ conflicting views, selecting an option is not obvious. Two prominent theories, ST and LQG, are not direct competitors but, if combined, might possibly be a TOE solution — a third-string revolution. Requirements were divided into those required and those not required. Background-independence, which is a key issue for a TOE, although most probable for a successful theory, is an optional requirement since spacetime may be a fundamental entity. And if it is, ST, using spacetime as a background, would be a viable option.

Also, current, and possibly future, experimental verification is not definitive. This may be inherent to any theory addressing Planck sized dimensions. As related to cosmology, both ST and LQG have proposals that satisfy initial conditions. There is some hope that ST will calculate the values of constants for SMPP and SMC (requirements three and four); but, both ST and LQG primarily rely on the multiverse as a solution. If experimental results from the Large Hadron Collider verified the existence of extra dimensions or supersymmetry, this would further endorse ST as the most likely option based on circumstantial evidence.

Even though ST is a leading candidate among the four options, we must acknowledge all options, even the last option, the possibility that no solution exists — if this option is valid, nature may have intentionally created an unsolvable puzzle.

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