Fundamental As Fewer Bits

Terry B. Bollinger [1]
[1] *Apabistia Research, Ashburn, VA, USA 20147*

(Incepted 22 January 2018; Published 8 February 2021; Tweaked 2021-06-30.18:29)*

A physics theory predicts precise experimental results for some set of naturally occurring phenomena. Consequently, every well-formed physics theory is equivalent to a computer program that uses input descriptions of specific experimental setups to generate the outputs expected from those setups. The *Kolmogorov complexity* (or *Kolmogorov minimum*) of such a computer program is the program that uses the smallest number of bits to represent the largest possible of such input-output data pairs accurately. The principle of *concise prediction* asserts that the theory whose program length is shortest for a given set of experimental inputs and results is the one most likely to lead to deeper insights and new physics.

DOI: https://doi.org/10.48034/20180122

This is about: Theoretical Techniques, Information Theory, Kolmogorov complexity, Data Analysis

I. THE WORLD'S MOST FAMOUS EQUATION

It is arguably the best-known equation in the world:

$$E = mc^2 \tag{1}$$

Its association with the genius of Albert Einstein [1] and the power of nuclear energy makes it unforgettable. It is the only physics equation that can be heard regularly in non-technical conversations as a shorthand for profound insight. Its message is easy to understand and seemingly paradoxical: Stodgy, static mass, and dynamic, moving energy are two aspects of a single quantity.

Another compelling feature of this famous equation is the breadth of its application in comparison to its brevity. It requires only three letters, a number, and two algebraic operators. It is also concise at the conceptual level by allowing the reader to realize that mass and energy are, at a deeper level, a single resource rather than two.

I. KOLMOGOROV COMPLEXITY AND THEORIES AS PROGRAMS

The brevity of $E = mc^2$ is not an accident. It is an example of *predictive conciseness* in physics. To understand why this is, note that physics is an experiment-based science that pairs input data points (e.g., m) with output data points (e.g., E). Thus, one way to express a physics theory is as an executable program that replicates all known data pairs for some class of natural experiments. This representation will usually but not always include extrapolations to data points yet to be measured, making the theory *predictive*. New theories such as special relativity emerge as new data forces abandonment of earlier theories that used smaller or less accurate data sets.

Before automated computers, theories were mixes of precise equations and informal instructions (papers) on how to use them. Implementing a theory as a computer program provides a more direct relationship between theories and their corresponding experimental data sets. In effect, it *compresses* that data into a much more compact form: the program itself. For example, Einstein's famous equation is the core of a universal program that captures data points for how matter and energy interconvert, literally across the full universe. If expressed as raw data points, this particular data set would be nearly infinite in size. This equation's power lies in its ability to compress such a vast set of data into such a small program.

The great mathematician Andrey Kolmogorov was the first to recognize the compression relationship between data sets and computer programs [2]. He noted that a compact program is a measure of the *information content* of the entire data set it generates. Based on a vast body of experimental data, Einstein's equation generates accurate mass-energy interconversion data pairs for all known physics, anywhere in the entire universe, at any scale of

This document uses Kenobi versioning. The online name always points to the most recent document version, while ob1, ob2,… suffixes indicate obsolete releases of the document.

size, from the beginning to the end of time. The degree of data compression implied by this equation is impressive.

Kolmogorov knew that programmers could encode the same data in vastly different ways, resulting in an infinite number of possible program sizes. However, he also proved that there exists a minimum size for such programs. This minimum program size is now known as the *Kolmogorov complexity* of a data set. This paper interchangeably uses the phrase *Kolmogorov minimum* to emphasize that this is a particular case of program length. Kolmogorov proved that even though features such as a lack of apparent patterns are indicators that a program is likely near this limit, proving the program has reached the Kolmogorov minimum is undecidable. The minimum thus can be approximated but not reached.

By translating a theory into a computer program, its *Kolmogorov measure* (program length in bits or bytes) roughly indicates how well it compresses the data set.

II. PREDICTIVE CONCISENESS

Suppose two theories perform equally well at predicting an experimental data set. When converted into formal programs, the theory with a shorter bit length is closer to the Kolmogorov minimum of that experimental data set.

The principle of *predictive conciseness* is that when two or more theories predict experimental data equally well, the theory with the shortest Kolmogorov measure is also the more *fundamental* of the two theories. In other words, the theory with the shortest program is also the one most likely to provide new insights into the universe's structure.

III. KOLMOGOROV COMPRESSION AS PATTERN RECOGNITION

Why should physics theory be related to finding the Kolmogorov minimum of experimental data sets? The shared factor is that both deal with how small sets of deep patterns generate enormous complexity. In mathematics, these small generative sets are called axioms. In physics, these small sets are called the laws of physics.

Both axioms and laws are, ultimately, patterns: Well-defined relationships between small numbers of persistent items. When expressed as digital data, these patterns take the form of bit sequences whose relationships to other bit sequences imbues them with meaning or *semantics*. The goal is to express sets of digitized experimental data as relationships between these more concise patterns.

To understand the relationship between deep patterns and Kolmogorov complexity, one must recognize that the concept of Kolmogorov complexity is intimately related to lossless data compression. A computer file is a set of data pairs that link abstract *n*-dimensional spatial locations to well-defined digital values. The goal in lossless data compression is to find the most compact, information-dense representation of the file's data pairs. [3] If the pairs are already entirely random, this task proves impossible, meaning that the file is already in its least-bits-possible or Kolmogorov minimum form.

If there is some form of repetition of a smaller pattern within the file, compression is possible by *factoring out* that pattern. Factoring consists of expressing the pattern only once and pointing to that one expression whenever the pattern occurs again in the file.

Kolmogorov recognized that this process of factoring out repeated patterns inevitably creates formal structure in the smaller version of a file. In the most potent cases, this structure has the form of a full-fledged computer program. Unexpectedly, all forms of data compression thus turn out to have computer program equivalents.

While the idea of compressing data by converting it into a computer program sounds exotic, the practice is quite common and occurs even in English. For example, how might one write a program to replace a one-gigabyte file containing one billion copies of the bit string 01001101? Ironically, the answer is in the question: "one billion copies of the bit string 01001101". Even in English, this phrase is precise enough to serve as an executable program capable of reproducing the original file. Since it uses only 45 characters or bytes, the result is a compression ratio of over 22 million to 1. A very modest effort to shorten this program even further gives "10^9*01001101" with a length of 13 bytes, which achieves a compression ratio of almost 77 million to one. Both programs are examples of attempts to approach the Kolmogorov minimum for the file. More subtly, both programs also postulate, possibly incorrectly, that an event in the past *generated* the larger file by making a billion copies of the smaller pattern.

This link between programming and postulating pattern sources connects the concept of Kolmogorov complexity to theoretical physics. Lossless data compression attempts to recreate a set of space-to-value computer data pairs by postulating a set of simpler patterns that generated them. Similarly, theoretical physics attempts to recreate all experimentally possible physics data pairs by postulating a set of patterns that generated them.

In both cases, each identification of a new pattern makes the challenge of finding another pattern harder still. For commercial data compression, more compression requires more time and more computer resources. For theoretical physics, theories that uncover the deepest patterns require more time and more insight.

IV. COMPRESSION AS AN EXPONENTIALLY HARDER ASYMPTOTIC LIMIT

Kolmogorov's original proof is a decidability argument. Unfortunately, it provides little practical guidance on why it is difficult to assess how close a given program is to its Kolmogorov minimum. Recognizing that a program being both compact and information-dense cannot disprove the presence of more patterns provides additional insights.

For example, the digit string 66276378959982317513 appears to be random and thus uncompressible. However, a broader search of mathematics shows this sequence is the 20-character substring of π beginning at position 39,025,353. Replacing it with the 14-character string $\pi(39025353,20)$ thus gives a nominal 30% compression.

There was nothing in the 20-digit sequence that hinted that it might be part of π, yet the definition of π turns out to be its best option for compression. The only way to find such cryptic opportunities is to broaden the search. Part of this search will necessarily involve representing the data in new ways that enable observation of hidden patterns.

Such examples suggest a strategic rule of thumb:

> *The closer one is to the Kolmogorov minimum, the more one must examine novel mathematical transformations and options to get to the next level.*

There is also a resource cost associated with the above rule, which results in this corollary:

> *As one gets closer to the Kolmogorov minimum, more resources, creativity, and tolerance for failure will be required to make further progress.*

For lossless data compression, these rules clarify why attempting to obtain near-maximum data file compression consumes more computer time and fails more often.

The more insightful application of these rules, however, is to physics theory. The history of theoretical physics has been one of conceptual consolidation, recognizing that unrelated phenomena are, on closer examination, actually different aspects of a single deeper pattern. [4] Examples include Newton's consolidation of gravity with planetary motions and the recognition in the 1800s that electricity and magnetism are aspects of electromagnetism.

For data file compression, such shared deeper patterns are called *factors*. For physics theories, they are more often called *symmetries*. [5] The underlying concept of pattern-based simplification is the same in both cases.

As noted before, finding deeper compression patterns becomes more complicated and uncertain as data files move closer to their Kolmogorov minimums. Similarly, uncovering deeper symmetries and consolidations becomes more complicated and uncertain as physics theories move closer to their Kolmogorov minimums. Thus, additional reductions in the size of such theories are more likely to require more interpretations, additional resources, and a higher tolerance for failure. Given these counter incentives, there is a tendency for theories to reach an equilibrium point where they are comprehensive enough to represent all known data but still relatively far from their Kolmogorov minimum. The Standard Model of particle physics is arguably an example of just this effect.

V. OPPOSING GOALS OF MATH AND PHYSICS

Defining physics as uncovering deep patterns from data on natural phenomena allows a sharp distinction between physics and mathematics. A mathematical discipline begins with full knowledge of its deepest patterns, called *axioms*, which are assumed to be correct by consensus. Mathematics thus begins at what it assumes to be the Kolmogorov minimum for all possible mathematical theories and expressions. Physics begins at the other end of the data compression spectrum by looking only at the data set of natural phenomena generated by some unknown set of axioms. From this vast data set, physicists attempt to derive the small set of axiomatic patterns (physics laws and symmetries) that generated them.

Mathematics thus is primarily generative, with the set of axioms *assumed* (whether correctly or incorrectly) to be valid. In contrast, physics is necessarily inductive and more susceptible to incorrect interpretations of the data set. For example, one cannot assume that even a well-accepted axiom from mathematics can safely be assumed true in physics. An actual example of this kind of axiomatic instability occurred when Einstein found it necessary to violate Euclid's fifth "parallel lines" postulate to create the curved spacetime of General Relativity. [6]

VI. THE RISK OF SIDE TRIPS: GNOT THEORY

So far, this analysis has focused on idealized scenarios in which theorizing is just a matter of uncovering every pattern in an experimental data set. However, a danger inherent in heuristic, hypothesis-based construction is that invalid theorems insert superfluous complexity (noise) by attempting to factor the data incorrectly. For both data compression and theorizing, the requirement that the original data set must be preserved forces this type of false theorem to induce a binary structure. On one side, the theorizer introduces a plausible but ultimately irrelevant theorem on how to factor the data set. On the other side, the theorizer must then, over time, ensure the original data set's fidelity by inserting an *anti-theorem* that exactly cancels the superfluous theorem's impact.

For example, here is an assertion about the relationship between mass and energy in the universe that is perfectly valid in terms of a vast body of experimental data:

$$E = -me^{i\pi}c^2 \tag{2}$$

The problem, of course, is that $e^{i\pi}$ is nothing more than a complicated way of saying -1. The equivalence of $e^{i\pi}$ to -1 is mathematically fascinating and can be highly relevant in other situations. However, in this context, it is an assertion that adds nothing to factoring the data and only makes the equation more complicated. Its presence complicates rather than promotes the task of finding the Kolmogorov minimum for the full set of experimental data pairs that describe energy-matter relationships throughout all of spacetime. Its canceling anti-theorem is the minus sign inserted in front of m.

The very simplicity of the example shows the danger. While a mathematician quickly recognizes the insertions' pointlessness, the *immediate* impression to a more naïve reviewer can be that the addition is attempting to convey an important new insight. It wastes time even when the reviewer quickly recognizes it as a null addition.

Intuitively, the zero-sum-game nature of such pro-anti theorem pairs should make them trivial to spot. In practice, uncovering them can challenging. Theorizers introduce theorems as well-defined events, hoping to find dramatic new factorings of their data sets. In contrast, anti-theorems more often arise over time due to subsequent repairs to ensure fidelity to the original experimental data set. Thus, canceling anti-theorems often take on the form of nebulous collections of fixes that lack apparent links back to the gratuitous theorem that generated them.

When a theorem fails to bring a theory closer to its Kolmogorov minimum, it is a *gratuitous null-outcome theorem* or *gnot*, pronounced *knot.* The word similarity is intentional since gnots and knots both transform straight paths into needlessly complicated, hard-to-untangle paths. The anti-theorem for a gnot is its *anti-gnot*. The gnot and its anti-gnot together form a *gnot pair*. Finally, a *gnotty* or *gnotted* theory is one with enough or sufficiently pervasive gnots to move it far away from its Kolmogorov minimum.

In terms of clarity and conciseness, gnots deep in a theory's infrastructure can be especially devastating. A deep-rooted gnot scatters the canceling anti-gnot over the theory's entire fabric, making it difficult to discern and remove. Even more insidiously, unquestioned acceptance of the original gnot can cause the development of a coherent anti-gnot to *become* the dominant focus of further theory work. Since a gnot pair is nothing more than a side trip caused by human error and, in some cases, outright presumption, the resulting waste of human and other theory development resources can be devastating.

VII. GNOT REMOVAL AS MAP NAVIGATION

In terms of reaching a theory that accommodates new data and is close to the Kolmogorov minimum for that data, gnot pairs are side-trips. As anyone who has taken a long driving vacation knows, side-trips can be beautiful. However, if the goal is to find the shortest path from point A to point B, side-trips are ultimately just a complication.

One way to represent this situation is to recognize that a Kolmogorov program's theorem components can act as unit vectors in a Hilbert (Euclidean) space. Vectors in the resulting space then represent the laws or subsets of laws for possible universes. However, only a few such vectors match the experimental data sets of our universe.

Figure 1 gives a graphical representation in this space of the impact of gnot/anti-gnot "side-trips" in this space. The first step in eliminating gnot pairs from a bloated theory is to make pairing and symmetries of gnots and anti-gnots as explicit as possible. Explicitly pairing gnots and anti-gnots makes their self-canceling nature readily apparent. The final step is to excise the pairs. Quantum computation algorithms capable of converging with exceptional speed using only simple code provide examples of how vast this trimming potential may be even for well-established quantum modeling methods. [7]

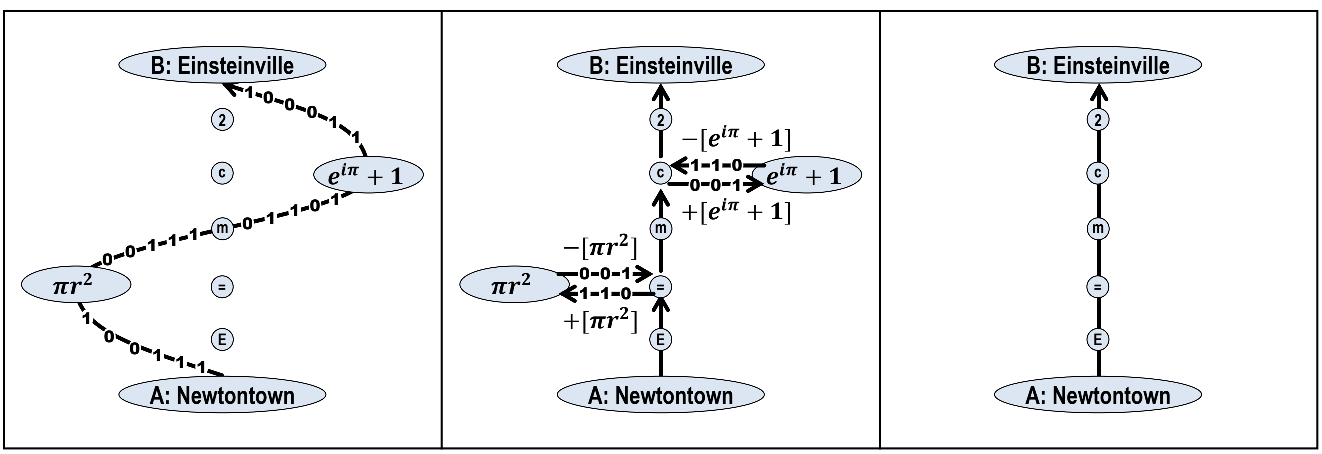

FIG. 1. Gnot removal as optimizing map navigation.

VIII. A REAL EXAMPLE OF A GNOT REMOVAL

In 2015, the late Steven Gubser, a contemplative and insightful string theorist at Princeton, gave a presentation at the Simons Foundation on "Quarks, Flux Tubes and String Theory Without Calculus." [8] The talk's central theme was that for nuclear (quark-based) physics, discrete spacetime models produce calculations that are as accurate as those of continuous spacetime models at a much lower computational cost. Gubser goes into considerable detail about a mostly forgotten point about string theory's origins on the way to that goal. The strings of what is now called string theory are math-only abstractions that vibrate in more than three dimensions and have experimentally inaccessible lengths of about 10^{-35} meters [9].

In sharp contrast, the original string theory of the late 1960s and early 1970s relied on massive sets of collider data on the masses of excited-spin hadron states, hadrons being particles composed of two (meson) or three (baryon) quarks. The masses of these excited-spin states closely resembled what would happen if the quarks were tied together by a powerful string and then spun around each other like a bola. Since the spin is quantized, the meson bola's various allowed spin states gave rise to a regular sequence of energies and particle masses. Figure 2 shows an example of this configuration for the J meson.

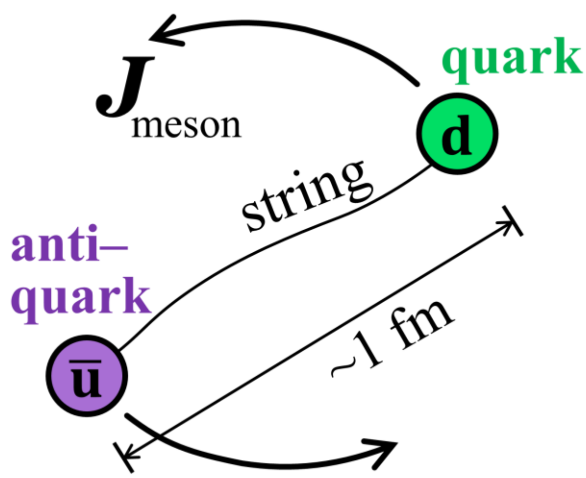

FIG. 2. Steven Gubser's 2015 diagram of the QCD string in a J meson. The string is a 1 fm (10^{-15} meter collimated bundle of color force attraction and electric force repulsion between a down quark and an anti-up quark. See video [8], starting at t=777 seconds (12:57 min:sec).

When data suggesting quantized string-like vibrations was first collected, neither quarks (the bola weights) nor the color force (the string) were known. The nature of the color force was significant since it later became apparent that, unlike the electric force, the attraction between two color-charged quarks is *constant* with increasing distance. This divergence from electric and gravity behavior is the main reason why color-charged quarks exhibit string-like behavior while spinning.

All of this hadronic string-like behavior takes place in *xyz* space at the tiny but accessible scale of 1 femtometer, or 10^{-15} meters. The need for quark bola weights and the details of the color force interactions severely constrains the range of possible string vibration solutions, allowing only the hadrons seen in collider data.

In one of the more remarkable leaps-of-faith in science history, string theory's next stage abandoned all "bola model" constraints and focused entirely on string vibration equations. [9] These fully abstract strings were no longer required to have particle weights at their ends and were no longer required to be composed of any known force, except possibly Planck-scale gravity if one arbitrarily assumes that gravity at that scale no longer falls off at r^{-2}. To increase the range of available solutions, the new string theory also places the strings in spaces with far higher dimensionality than *xyz*. Finally, it shrinks the strings of an unknown force by *20 orders of magnitudes* to 10^{-35} meters, nominally to support a quantization of gravity that never occurred in the next half-century. Figure 3 summarizes the assumptions required by the new strings.

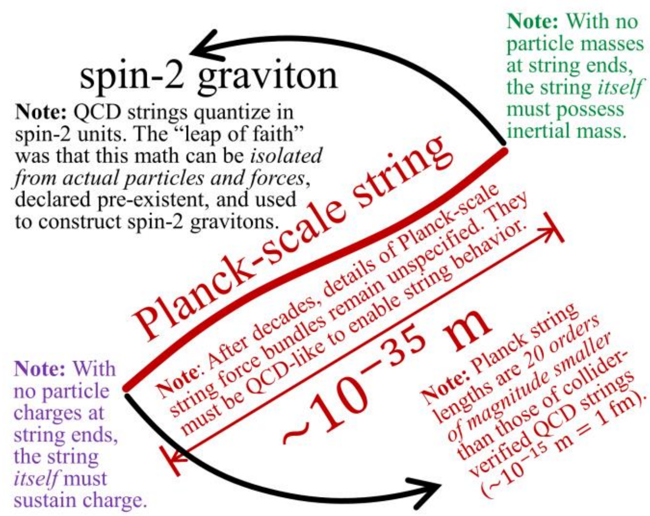

FIG. 3. The transition from collider-data-based, experimentally verifiable to abstract Planck-scale strings required numerous assumptions. The faith-based assumption that math is in some sense more "real" than experimental results is at the center of these assumptions.

The remarkably casual fashion in which the proposers of these new strings abandoned known-force and particle-termination specificity in favor of abstract strings built from unknown strong-like forces with no particles serve as well-defined endpoints physics is baffling in retrospect. A direct consequence of this complete unfettering of the associated math from both experimental data and the fairly ordinary *xyz* 3-space constraints of an actual string with actual endpoints is an explosion in the number of possible vacuum states or vacua unleashed. This number appears to grow without any exact bounds as more analyses emerge, going from 10^{500} in 1999 to $10^{272,000}$ in 2015.

However, at that time, a fully “black box” approach to explaining particle physics called S-matrix still held sway over much of the research community [10].

The new strings are experimentally untestable, in stark contrast to data-derived hadronic strings. Due in no small part to Planck string theory’s inherent untestability, the entirety of modern string theory has made no discernable contribution to compressing physics data sets derived from actual experiments.

The specific example of pro-anti gnot removal from Gubser’s presentation is not Planck string theory itself, however, but in how he uses concepts from string theory to explain *asymptotic quark freedom* in hadrons. [11]

The simplest conceptual way to understand asymptotic quark freedom is to think of the QCD string that connects two quarks as having a fixed minimum length. Above that length, which is about one femtometer, the string is elastic with a high and linear energy cost. Below that length, the string goes slack and gives asymptotically less attraction.

While the string model thus provides a good conceptual model of *how* asymptotic quark freedom behaves, it does not provide a very satisfying explanation of why color force attraction should behave in such an odd way. Gubser proposed an ingenious mechanism for applying the full range of Planck-scale strings concepts to bear on the asymptotic freedom of QCD strings, which again are 20 orders of magnitude larger. His proposal is in Figure 4.

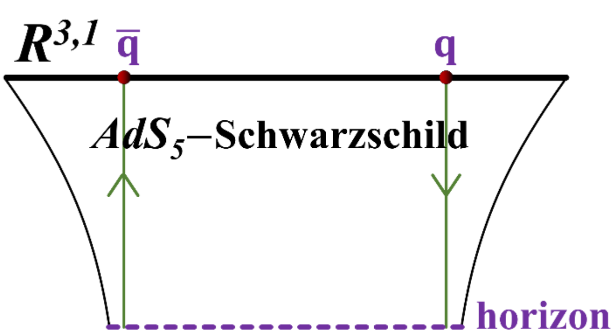

FIG. 4. Steven Gubser’s 2015 proposal that asymptotic quark freedom is a consequence of QCD strings traveling to and from the black-hole event horizon of holographic (AdS_5) projection space. See video [8], starting at t=1168 s (29:18 min:sec). The arrows to and from the event horizon are a particularly vivid example of a pro-anti gnot pair. In particular, the vast fabric of general relativity invoked by the event horizon plays no role in compressing experimentally derived QCD data sets.

Given that these are the same quarks seen in protons and neutrons, it can be startling to realize that the *horizon* at the bottom of the figure is essentially the same concept as the event horizon caused by gravitational collapse under general relativity. One might be forgiven for wondering why a concept generally associated with massive black at galaxies cores is showing up, at least mathematically, inside every proton and neutron of one’s own body.

The source of this juxtaposition is the *holographic principle*, an idea first proposed by Nobel Laureate and Gerard ’t Hooft [12] and later expanded upon by Leonard Susskind [13]. Just as one can use 2D film to capture 3D images holographically, ’t Hooft’s holographic principle asserts that there exists a type of 2D surface that can, in principle, encode the entire universe’s spatial or *xyz* state. Mathematically this surface looks like the event horizon surface of a black hole. The 3D view and the 2D event-horizon view become two ways to view the same universe.

Gubser recognized that this holographic equivalence must work even at the scale of individual hadrons. The ordinary spacetime representation of the quarks and meson lies at the top, while their holographic representation is at the bottom. His innovative idea was that at close range, the QCD string breaks into two parts, with each half linking instead to the event horizon. This break means that the quarks no longer see each other at distances significantly less than one femtometer, resulting in asymptotic freedom.

Curiously, Gubser’s proposal is more robust because it does not explicitly invoke the exceptionally physically vague concept of Planck-scale strings. While ’t Hooft’s event horizon projection concept assumes the same Planck scale as such string, it only invokes this scale as a way of quantizing gravity. By stating his holographic asymptotic freedom theorem entirely in terms of how experimentally real particles, forces, angular momentum, and distances work with ’t Hooft’s proposed holographic horizon, the result stays at least potentially testable.

IX. GNOT SO FAST

However, the issue is not the mathematical or logical plausibility of this innovative theorem but something much more specific: Does it reduce the Kolmogorov program’s size for capturing all known data on the effect?

One could devote a great deal of analysis and potentially numerous papers to this question if desired, but the simple answer is, *of course not*. The goal is to reduce Kolmogorov program size for hadron behavior, specifically for the issue of asymptotic quark freedom.

X. THE TRAMPOLINE EFFECT

Note that the closer one moves to the straight path Kolmogorov minimum in a state change map, the harder it becomes to find further simplifications. This can happen even when too many arbitrary constants, too much reliance on raw data, or unexplained features suggest that further simplifications are needed. The unsettling truth in most such cases is that theorists are making wrong assumptions about what is “fundamental” or “atomic” and what need to be broken down farther.

Unfortunately, this resistance to further compression when approaching Kolmogorov minima can easily lead to what I call the trampoline effect: Bouncing *off* of the near-minimum region by adding new ideas that seem relevant, yet in the end just add more complexity and more curves. The result is to create theories that in effect bounce off the taut Kolmogorov minimum path and instead send theorists out on far and sometimes fascinating side trips, but ones that ultimately have very little to do with the original simplification problem. One of the signs that this has happened is when the literature for a topic that once requires only few concentrated pages of math to describe suddenly explodes into a huge spectrum of papers and ideas that no longer converge to any obvious resolution of the original problem.

The trampoline effect helps explains the baffling sequence of events that ensued after completion in the 1970s Standard Model of particle physics. Judging by its remarkable predictive success and relatively small size, the 1970s model likely was already relatively close to its Kolmogorov minimum. [14] Attempts to shrink the Standard Model further instead resulted in a spectacular explosion of almost entirely untestable and heavily mathematical papers, with *string theory* [15] [16] in particular dominating theoretical physics research for decades. One indicator that this was a trampoline bounce is that the Standard Model was left largely unaffected.

XI. THE SPEKKENS PRINCIPLE

Robert Spekkens contemplated something very close to the trampoline effect in his 2012 FQXi essay [17] when he addressed the curiously complementary relationship between using bits to describe where a particle "is" at a given moment — its "kinematic state" — and how that particle and its state changes as it moves into the future — its "dynamics." The principle that Spekkens recognized was that the kinematic and dynamic descriptions in quantum theories could take on dramatically different forms as long as the two sides remain complementary in some more profound fashion. From this, Spekkens speculated that there must exist a more fundamental fulcrum point. These various pairings of kinematics and dynamics emerge, much as in the mutually canceled side paths I describe for the trampoline effect. He even proposed a specific approach, causal structure, as a starting point for uncovering this theoretical fulcrum. In Kolmogorov terminology, the fulcrum that Spekkens postulated would be the Kolmogorov minimum for quantum theories, and the various interpretation pairs would be examples of "side trips" into areas that theorists such as John Bell [18] (a pilot wave advocate) and David Deutsch [19] (a many-worlds advocate) felt needed to be addressed.

XII. THREE CHALLENGES

I would like to end this essay with three challenges, two of which originated with Nobel Laureate Richard Feynman, and one of which originates broadly with the particle physics community.

> **Challenge #1**: What is the full physics meaning of Euler's identity, $e^{i\pi} + 1 = 0$?

One of Richard Feynman's distinguishing traits was his exceptionally good nose for the profound, and he found Euler's identity enthralling. [20] Why? Because it compactly connects four (or five) of the most fundamental and profound constants in all of mathematics: e, i, π, 1, and implicitly -1 by subtracting 1 from both sides.

Euler's identity is already arguably the basis for much of the mathematics used in quantum mechanics, since it is the starting point for expressing wave mechanics in an exceptionally elegant and compact form. However, my challenge (not Feynman's *per se*) is a bit different: I am asserting that due to its extreme brevity, Euler's identity is most likely an overlooked example of a Kolmogorov minimum relevant to the physics of our universe. My postulate is that we don't think of Euler's identity as physics only because we do not yet understand how it maps into experimental reality. Identifying such connections might lead to some new factoring of physics in general and of quantum mechanics in particular, one in which Euler's identity pops out and brings together concepts that previously were thought to be unrelated.

> **Challenge #2**: What is the simple explanation for fermion-boson spin statistics?

For over 20 years, Richard Feynman thought about what seems at face value to be an amazing coincidence. [21] All known fundamental particles in physics fall into one of two categories: fermions that refuse to share the same state, and bosons that love to share the same state. Fundamental fermions include electrons, quarks, and neutrinos, and also composite protons such as neutrons. These fermions form what we call matter. Fundamental bosons include photons and gluons, and are the basis both for energy (e.g. a beam of light) and, in virtual form, fields (e.g. electromagnetic fields).

Every fundamental particle also has a quantized form of angular momentum called spin, and its spin has a fascinating relationship to these two families. Particles that include a very strange and originally unexpected form of angular momentum called ½ spin are always fermions, while particles that use only the much more understandable whole integer spins (e.g. 0, 1, or 2) are always bosons.

The question that troubled Feynman for decades, and which he never was able to answer to his own full satisfaction, was this: What is the *simple* explanation for this connection between spin and the two families of particles?

I should hasten to note that the necessity of this correlation was proven decades ago, so in that sense it is not a mystery! The problem that troubled Feynman was that for so simple a rule, there should also be a similarly simple explanation. The current proofs of the connection are anything but that, requiring pages of complicated arguments that leave the reader thinking no better off in terms of understanding *why* such a thing should be so.

Given that the very concept of spin ½ is nonsensical when applied to ordinary three-dimensional space, the lack of simplicity in this case likely stems from our inability understand what spin ½ really means at a deeper level. The great early quantum physicist Wolfgang Pauli unfortunately became so frustrated with his own inability to resolve the spin ½ issue that he finally (and angrily, as was his tendency when frustrated) declared it a "property" of quantum systems that had no need for further analysis by him or anyone else. Pauli thus set up a pattern that persists strongly to this day of simply ignoring one of the most fascinating clues in all of physics, which is the existence in all fermions of a type of angular momentum that *makes no sense* from any classical perspective.

The second challenge thus is to stop treating this astonishing half-spin mystery as "irrelevant" and instead seek out a deeper, more *fundamental* understanding of how half spin can even exist in our universe. After all, if you have a mysterious behavior (in this case "why do fermions refuse to share the same state?") that is firmly and profoundly attached to an even more mysterious and opaque box ("what exactly is half spin?"), the odds are quite good that figuring the mystery of the box works will also provide insights into the unique behavior associated with that box.

Challenge #3: Refactor the Standard Model *without* gravity.

Evidence for its incompleteness shows up vividly in its large number of arbitrary constants and baffling givens, such as why there are three generations of fermions. [14] The existence of more massive versions of common particles was so unexpected that when theorist Isidor I. Rabi first heard about the muon, which is the heavier second-generation version of the electron, he joked, "Who ordered *that*?" [22]

Recognition in the late 1970s of the need to factor the Standard Model further led, unfortunately, not to a search for Kolmogorov simplicity, but the axioms-dominated and primarily generative approach known as string theory, in which the mind-bogglingly large vibration modes of tiny strings and loops in higher dimensional spaces are assumed to explain not just the particles and fields of the Standard Model, but also gravity. Curiously, although decades of effort in string theory have produced an enormous number of often very arcane, hard-to-understand papers, what it has not produced are any simple or convincing insights into the most blatant unexplained features of the Standard Model, such as why the three generations of fermions even exist.

One factor in why string theory and related efforts to explain the Standard Model became so complex is their insistence on including gravity. Because gravity is so weak, principles of quantum mechanics drove the scale of such models into both extremely small length scales and extraordinarily high energies. This in turn helped unleash so many new options for "exploration" that the original Standard Model simply got lost in an almost unimaginably large sea of possibilities. [16]

Thus my suggestion for anyone interested in bit-reduction refactoring the Standard Model is simple: *Stop trying to include gravity in the refactoring*. Instead, take what was already in the 1970s original version and look for novel ways to factor it that reduce its size instead of expanding it. Furthermore, take issues such as the half-spin conundrum and the existence of three fermion generations as first-order clues that need to be integral parts of the final explanation.

Another strategy is to look for unexpected symmetries, but this time *without* insisting on using group theory first. While powerful, group theory is like software: It only takes what you put into it. If what you feed into the powerful machinery of group theory ignores or skims over issues such as why ½ spin exists, or why there are three fermion generations, it guaranteed that whatever sausage comes out the other end of your symmetry grinder will be just as oblivious to these issues.

Regarding gravity, here's a thought: If someone can succeed in uncovering a smaller, simpler, more factored version of the Standard Model, who is to say that the resulting model might not enable new insights into the nature of gravity? A more fundamental quantum model of the fermion and bosons could for example point to emergent effects relevant to gravity. There are after powerful theoretical reasons for arguing that gravity is *not* identical in nature to the other forces of the Standard Model. That reason is the very existence of Einstein's General Theory of relativity, which explains gravity using geometric concepts that bear no significant resemblance to the quantum field models used for other forces. Focusing on clarifying the relationships of the clearly quantum forces thus might open up opportunities to clarify why gravity looks so different, in ways that embrace and complement the geometric power of General Relativity instead of ignoring it.

XIII. FINAL THOUGHTS

Simplicity is as important now as in the early 1900s golden age of relativity and quantum theory. Physics as a message from the universe suggests that the best way to uncover new patterns is by pulling on unexplained dangling threads, not elaborating unverifiable axioms into massive edifices. Too often, such threads in physics have been dangling so long that no one bothers to look at them closely anymore.

The first step in re-examining a dangling thread is to review the details of any high-quality experimental data relevant to that thread. A single obscure but persistent detail in such data can become the unexpected clue that reveals a critical conceptual barrier, one that previously blocked all progress. With hard work and insight, one may then find a hidden gemstone of simplicity.

[1] A. Einstein, "Does the Inertia of a Body Depend on its Energy Content?," *Annalen der Physik,* vol. 18, p. 639–641, 1905.

[2] A. N. Kolmogorov, "Three Approaches to the Quantitative Definition of Information," *Problemy Peredachi Informatsii,* vol. 1, p. 1–7, 1965.

[3] K. Sayood, Introduction to Data Compression (Fifth Edition), Morgan Kaufmann, 2017.

[4] D. Muller, "What is NOT Random?," *Veritasium,* 16 7 2014.

[5] S. Haywood, Ed., Symmetries and Conservation Laws in Particle Physics: An Introduction to Group Theory for Particle Physicists, World Scientific, 2011.

[6] A. Einstein, "The Foundation of the Generalised Theory of Relativity," *Annalen der Physik,* vol. 354, p. 769–822, 1916.

[7] J. M. Sellier, "A Signed Particle Formulation of Non-Relativistic Quantum Mechanics," *Journal of Computational Physics,* vol. 297, p. 254–265, 2015.

[8] S. S. Gubser, "Quarks, Flux Tubes and String Theory Without Calculus," *Simons Foundation,* 9 12 2015.

[9] J. Scherk and J. H. Schwarz, "Dual Models for Non-Hadrons," *Nuclear Physics B,* vol. 81, p. 118–144, 1974.

[10] G. F. Chew and S. C. Frautschi, "Principle of Equivalence for All Strongly Interacting Particles within the S-Matrix Framework," *Physical Review Letters,* vol. 7, p. 394, 1961.

[11] D. J. Gross and F. Wilczek, "Ultraviolet Behavior of Non-Abelian Gauge Theories," *Physical Review Letters,* vol. 30, p. 1343, 1973.

[12] G. 't Hooft, "Dimensional Reduction in Quantum Gravity," *arXiv preprint gr-qc/9310026,* 1993.

[13] L. Susskind, "The World as a Hologram," *Journal of Mathematical Physics,* vol. 36, p. 6377–6396, 1995.

[14] N. G. Cooper and G. B. West, Eds., Particle Physics: a Los Alamos Primer, Cambridge University Press, 1988.

[15] L. Smolin, The Trouble with Physics: The Rise of String Theory, the Fall of a Science, and What Comes Next, Houghton Mifflin, 2006.

[16] B. Greene, The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory, Vintage, 1999.

[17] R. W. Spekkens, "The paradigm of kinematics and dynamics must yield to causal structure," in *Questioning the Foundations of Physics,* Springer, 2015, p. 5–16.

[18] J. S. Bell, Speakable and unspeakable in quantum mechanics: Collected papers on quantum philosophy, Cambridge University Press, 1987.

[19] D. Deutsch, The Fabric of Reality, Penguin Books, 1997.

[20] R. P. Feynman, R. B. Leighton and M. Sands, The Feynman Lectures on Physics, Volume I: Mainly Mechanics, Radiation, and Heat, vol. 1, Caltech, 1963.

[21] R. P. Feynman, S. Weinberg, R. MacKenzie, P. Doust and S. Weinberg, Elementary Particles and the Laws of Physics: The 1986 Dirac Memorial Lectures, Cambridge University Press, 1987.

[22] M. Bartusiak, "Who Ordered the Muon?," *New York Times,* 27 9 1987.