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God's Thoughts: Practical Steps Towards a Theory of Everything

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In 1922, Einstein was speaking to young Esther Salaman during a long walk; she was talking of her dreams and goals and he was sharing some of his thoughts. Among thoughts of travel, he described his core guiding intellectual principle when he said "I want to know how God created this world (wie sich Gott die Welt beschaffen). I'm not interested in this or that phenomenon, in the spectrum of this or that element. I want to know His thoughts; the rest are just details." [1].

No matter your opinion on religion, whether you are a staunch believer or an unapologetic atheist, that phrase "God's thoughts" is a delightfully poetic one. It represents in a metaphorical way nothing less than an understanding of the deepest and most fundamental laws of the universe. Specifically, the hope is that we will one day be able to explain all the kaleidoscope of matter and phenomena that we see as we look around us as arising from a small number of building blocks and perhaps a single force. This is would no doubt be a breathtaking achievement, but it is highly improbable that it will be achieved soon. Instead, it is more likely that we will make incremental advances that one day might lead to success. In this article, I'd like to review what we know so far and draw your attention to holes in our current theories that might provide clues to the next big advance. This is the core thrust of this article; rather than

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speculating on an improbable and grand advance, it concentrates on realistic progress we might make over the next few years.

Broadly speaking, there have been two parallel and mostly independent thrusts towards an understanding of the cosmos. The first is a theory that governs the quantum world and the second is a theory of gravity that explains the cosmos on the grandest scales. Jumping ahead, so you know what I'm talking about, these two extraordinary intellectual achievements are the standard model of particle physics and Einstein's theory of general relativity. I wish to briefly sketch both of these ideas before talking about the challenges and clues scientists are using to take the next step towards a theory of everything.

The Standard Model

The Standard Model is an amalgam of many better known theories. It includes one of the most impressive of scientific advancements, specifically Maxwell's equations, which unified both electricity and magnetism, but also explained the classical theory of light. The Standard Model also includes quantum mechanics, which finally explained the patterns seen in the chemical periodic table and made clear such things as the spectrum of light emitted by glowing gases and the details of how atomic and chemical bonds actually work.

The story of quantum mechanics has been told many times before [2]. Planck, deBroglie, Schrodinger, Heisenberg, Bohr and all the other familiar names worked out the quantized nature of the atom, while Hertz, Young, Einstein and others winnowed out the nature of the photon. Thompson, Rutherford, Chadwick and their contemporaries discovered the components of the nuclear atom. This pantheon of great minds taught us that all of chemistry could be explained as an endless combination of three particles: the proton, neutron and electron, governed by the rules of quantum mechanics and the force of electromagnetism. So this was already an incredible simplification in our understanding of the world. Three particles, one force, and some quantum principles explained the behavior of matter.

Of course this understanding was incomplete. The 20th century brought with it the discovery of radiation of a variety of forms. Rutherford's nuclear atom consisting of protons and neutrons could not be explained by electromagnetism. Indeed, a simple calculation of the repulsive electromagnetic force between two adjacent protons shows that the magnitude is 90 N or 20 pounds. Given the stability of atoms, this clearly pointed to the existence of an even stronger attractive nuclear force. The observation of beta radiation implied yet another nuclear force, one that is much weaker than the others. These three forces, electromagnetism and the weak and strong nuclear forces, cover the known forces of the subatomic realm.

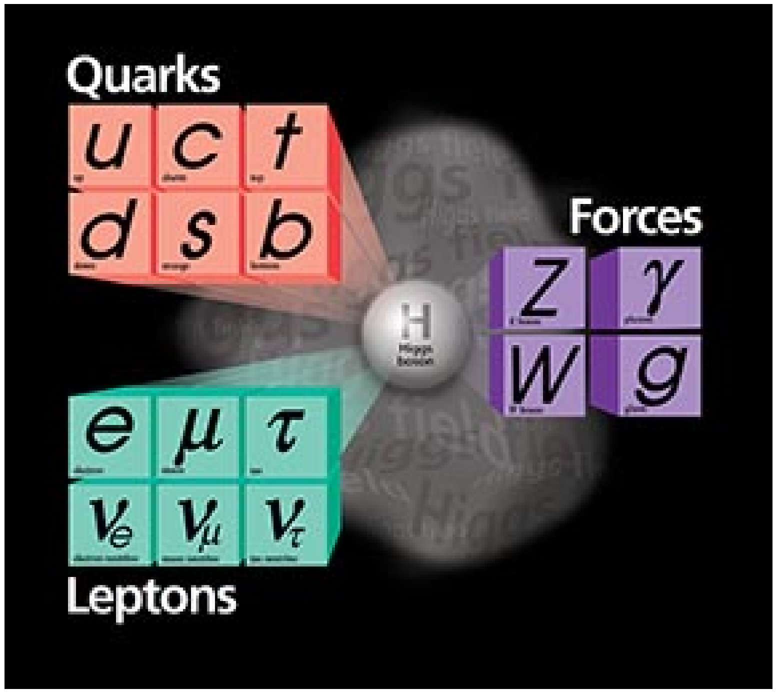
The period of time ranging from the 1930s through the 1960s further complicated our understanding of the microcosm. First in ghostly traces left by cosmic rays from space in primitive detectors high on mountains, followed by experiments using particle accelerators, scientists learned of hundreds of different kinds of ephemeral particles that played no real role in our world. These new observations required that additional theories be added to our slowly accreting model of matter. Quantum mechanics was merely just the start of the process.

In 2016, we have combined these observations and built a sophisticated model of the subatomic realm. No longer are the protons and neutrons fundamental building blocks, although the electron still retains that title. Protons and neutrons consist of smaller particles called quarks. There are six known quarks, with whimsical names. The up, charm and top quarks all have electrical charge of +2/3 that of the proton, while the down, strange and bottom quarks have an electrical charge of -1/3. The up and down quarks are found in protons and neutrons, while the others are short-lived and must be created in particle accelerators. The range of the mass of quarks is large, from the lightweight up quark, with a mass of less than one percent of that of the proton to the super heavy top quark with a mass of about 183 times heavier than a proton.

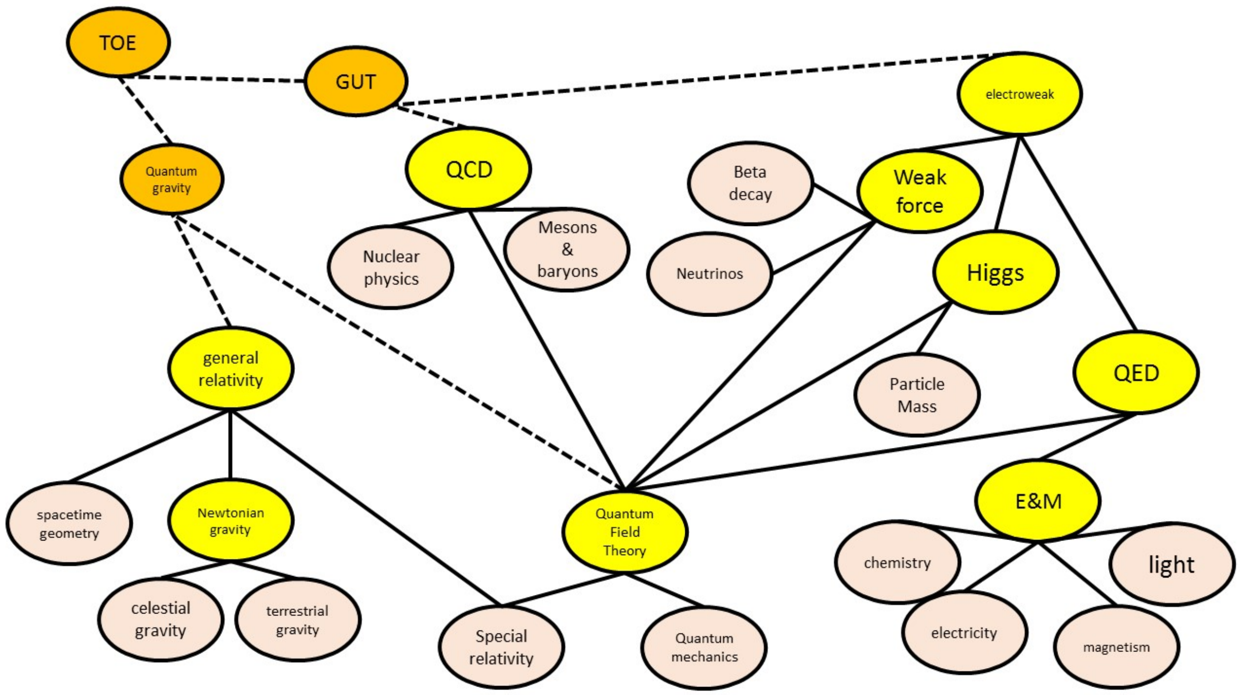
There are also particles called leptons, of which the electron is the most familiar. There are six leptons. Three of them carry electrical charge: the electron, muon, and tau, and all of them have the same charge. The other three are called neutrinos, and they have no electrical charge at all. The quarks feel all known forces, while the charged leptons do not feel the strong force. Neutrinos are ghosts of the subatomic world, feeling only the weak force and gravity, which is negligible in the quantum realm..

The three known subatomic forces all have quantized theories which incorporate Einstein's theory of special relativity. Each force requires at least one force-carrying particle to mediate the force. Electromagnetism has its photon and is described by the theory of Quantum Electrodynamics. The strong nuclear force is described by the theory of Quantum Chromodynamics and is carried by the gluon. And finally, the name of the theory of the weak force is just "the theory of the weak force." The particles that transmit the weak force are the W and Z bosons.

These twelve matter particles, combined with four force carrying particles (the photon, gluon and W and Z bosons) form the basis of our modern understanding of matter. Our understanding is completed with the addition of the Higgs field, first postulated in 1964 and discovered in 2012. The Higgs field and associated Higgs boson gives mass to fundamental subatomic particles and is shown in figure 1. The Higgs field plays a role in unifying electromagnetism and the weak force, showing that they are different ways to look at a deeper and more fundamental force called the electroweak force, as illustrated in figure 2. This is analogous to how it was not initially obvious that electricity and magnetism were really components of electromagnetism.



Caption: Figure 1: The standard model of particle physics consists of six quarks, six leptons, four force carrying particles and the Higgs filed that gives them all mass. **End caption**



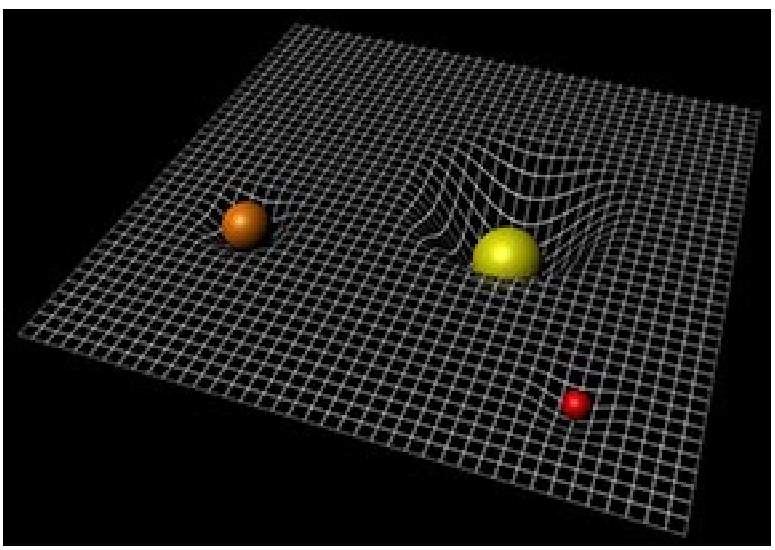
Caption: Figure 2: The history of unification has combined many phenomena to merely a few: gravity (general relativity), the electroweak force, and QCD. The yellow ellipses and solid lines denote known connections, while the orange ellipses and dashed lines are speculative unifications and connections. The pink ellipses indicate more basic observations from which the known unifications originate. **End caption**

Taken together, these particles and forces form the standard model of particle physics [3], which is our most modern understanding of the subatomic world. Using these particles and these forces, we can describe everything we've observed, from how birds fly, to how an iceberg floats, to how the sun burns. This is truly a triumph of the human intellect.

General Relativity

However, the standard model is quite silent on the most obvious force in the cosmos: gravity. In fact, we know nothing of the nature of gravity in the quantum world.

Which is not to say that we know nothing of gravity. Starting with Newton's unification of celestial and terrestrial gravity in the late 17th century, Einstein changed everything when he successfully elucidated the nature of gravity as being caused by the bending of space and time by energy and matter, as illustrated in figure 3. He described gravity as essentially being the geometry of the universe. This theory of general relativity can explain the orbit of the planets, the spin of galaxies, the depths of black holes and the expansion of the universe itself [4].



Caption Figure 3: Einstein's theory of general relativity cast gravity as a manifestation of the bending of space and time. More massive objects (i.e. high concentrations of energy), distort spacetime more and less massive objects are forced to travel in straight lines in that distorted geometry. **end caption**

Towards a theory of everything

Taken together, the standard model and general relativity form our current best theory of everything. They explain and predict the outcome of countless measurements. However, neither individually, nor taken together, do they form an actual theory of everything. There are many reasons for that. For one thing, general relativity falls apart when applied to the quantum realm. Under these conditions, the equations predict impossibilities, like infinite energy and probabilities exceeding 100%. But this is just one indication that these theories are incomplete. We don't know why there are six types of quarks and six types of leptons, when two of each is sufficient to describe ordinary matter. It could be that in the same way that molecules contain atoms and atoms contain protons, neutrons and electrons, that the quarks and leptons are composed of even smaller things. Possibly the patterns of quarks and leptons can be explained by building blocks that are smaller both in number and in size [5].

We also don't know why there are so many forces, when we hope that a final theory needs but one. While that is a theoretical prejudice, it follows a historical trend, with the unification of celestial with terrestrial gravity, electricity with magnetism, and finally electromagnetism with the weak force. Maybe the electroweak force and the strong force might be unified into what we provisionally call a grand unified theory or GUT. And, dreaming big, a GUT and gravity might be unified into a single theory of everything or TOE.

It's clear what the dream of a theory of everything would entail. A single building block, governed by a single force, is the big goal. And it would be ideal if the theory made it clear why things are the way they are and no other. Essentially, we would hope that somehow the definition of a universe gives no options other than the cosmos in which we live. This has often been described as unifying all phenomena to the point that the final equation can be written on a t-shirt.

So how will we proceed? Well in many popular treatments, what is presented is the conceit that someday in the next few years that a genius will come up with an idea that fits the bill. Even in the recent past, a theory called superstrings was popularized which postulated that the ultimate building block is a single microscopic string about 10^{-35} meters in size. The matter and force carrying particles would then just be different vibrational patterns of that single type of string. This idea is attractive, because it is intellectually compact and further there have been some theoretical advances of the idea. However, the natural energy realm for this theory is 10^{15} times higher than accessible by the Large Hadron Collider (LHC), which is the highest energy particle accelerator ever built. And this should raise a mental flag for you. For instance, think about the vast range of phenomena that exists between the LHC energy scale (10^{13} eV) and one a factor of 10^{15} lower (10^{-2} eV). That lower energy scale describes the weakest of chemical bonds. But between the two, there is the nature of the atom, nuclear physics, radiation, and high energy particle physics. It beggars the imagination that scientists won't encounter new phenomena that nobody ever expected as they try to achieve collision energies at the superstring scale. So it seems to me that developing a theory of everything given only what we know now is an overly ambitious goal. So what about a more practical approach?

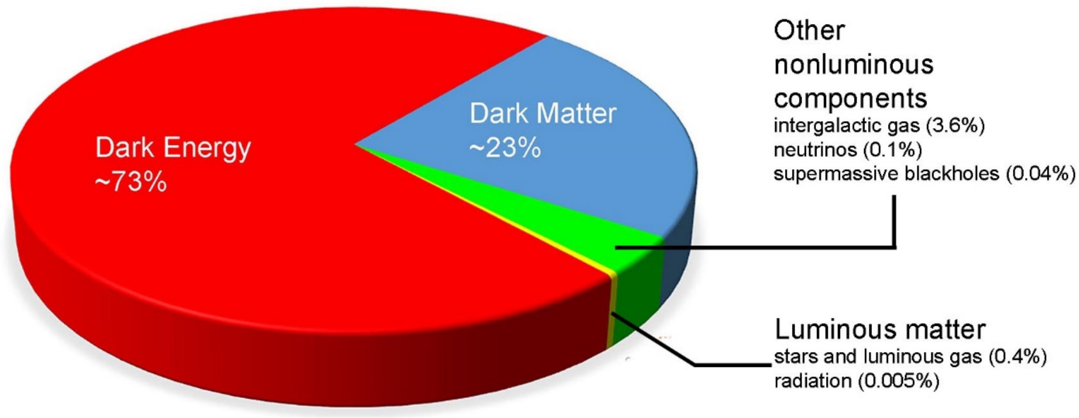
Baby steps

As modern physicists mull over what a theory of everything must be, it is important to remember that our theoretical understanding of the laws of the universe has been stagnant for nearly fifty years since the standard model was developed and over a hundred years since Einstein intuited his insightful ideas on gravity. This is because these two theories have done a superlative job describing most measurements. But there are unsolved mysteries. And that is where we must turn our attention. For just as a tug on a loose thread can unravel a sweater, maybe one of the phenomena unexplained by modern science might just allow theoretical physicists to knit a better model.

So what are the most burning unsolved questions and what are ideas that scientists are exploring that might explain them?

The Dark World

The Standard Model explains essentially all phenomena observed in the world of ordinary matter, which is to say the world of atoms. However, perhaps one of the most humbling realizations of modern physics is that the matter of atoms is but a mere ~5% of the mass and energy of the universe. Over the last twenty years or so, scientists have realized that there are two other substances that dominate the cosmos. They are called dark matter (~23%) [6] and dark energy (~73%) [7], as shown in figure 4. Dark matter is a form of non-luminous matter that is invoked to explain why galaxies rotate faster than can be explained by the known laws of physics and the observed luminous matter, as well as to explain the internal dynamics of large clusters of galaxies. Dark energy is an energy field in the universe that is causing the expansion of the universe to accelerate. A form of dark energy called the cosmological constant was proposed in1917 by Einstein as a mechanism to rescue his newly-developed theory of general relativity, which seemed to predict a dynamic universe and ran afoul of the theoretical prejudices of the time of a static and eternal cosmos. With the observation in 1929 of the expansion of the universe, the cosmological constant was abandoned, only to experience a renaissance in 1998, when the universe was observed to be not only to be expanding, but to be accelerating. The name “dark energy” was coined in April of that year.



Caption: Figure 4: The mix of ordinary matter, dark matter and dark energy depends on cosmic time. The fractions shown here denote estimates of our current universe.
end caption

To appreciate the importance of achieving an understanding of the dark sector on developing a future theory of everything, we need to understand the range of proposed explanations. For instance, in dark matter, the broad theoretical consensus is that dark matter is a particulate form of matter, with individual particles having a mass of 10 to 1,000 times heavier than a proton, being stable on the timescale of the universe and having no electric charge or quark content. Earlier proposed explanations included modifications of the laws of inertia or gravity, which would clearly point in a very different direction in regards to what a theory of everything would look like as compared to the particulate explanation. These gravitational and inertial explanations fell in disfavor with the observation of the Bullet Cluster [8], the collision of two large clusters of galaxies and the properties of which favor the particulate explanation of dark matter. However, the recent non-observation of dark matter by the LUX experiment [9]is giving pause to the theoretical community and they are taking another look at theories of modified gravity. There are other viable explanations of the dark matter conundrum. One involves the idea of superfluidity, which suggests that dark matter is a superfluid in parts of the universe and a normal fluid in others [10]. A second idea postulates an ultra-light particle called the axion [11] that has been proposed to explain mysteries in the strong force. A third interesting idea is called complex dark matter [12] and predicts that dark matter is just as varied as ordinary matter and even postulates a dark charge which binds together dark matter in complex structures. In the same manner in which dark matter is unaffected by familiar electric charge, ordinary matter is blind to dark charge. In short, we really don't know what the final answer will be for the dark matter question.

On the dark energy side, things are perhaps a little simpler. The current and simplest model of dark energy is the form proposed by Einstein, called the cosmological constant. As the name suggests, this form of energy is constant, but constant in density, not total energy. Thus, as the universe expands, the amount of dark energy is growing. This non-intuitive feature is allowed in general relativity. The fundamental nature of dark energy appears to be that it is a property of space itself, although it could have a different origin. While the cosmological constant is a popular idea, there is also a proposed alternative theory. This other possible explanation for dark energy postulates an energy field called quintessence, which has similar properties as the cosmological constant, but slowly varying in time [13]. The question of whether dark energy is varying or constant has profound consequences on our predictions on the past history of and future behavior of the entire universe. Muddying the waters are a recent publication that claims that the accelerating expansion of the universe is not real [14]. This publication has not been embraced by the scientific community, but underscores the range of uncertainty of possible explanations.

In short, any theory of everything will need to supply answers to the conundrums of the dark sector and it would be a very ambitious accomplishment to build such a theory.

Mysteries of the Standard Model

The standard model is a very successful theory, but it is not complete. While it explains, light, chemistry and radiation, there are many questions it doesn't answer, like the questions of patterns in quarks and leptons. But there are some other very big unanswered questions. For instance, in the standard model, the neutrinos are massless. However, with the observation of neutrino oscillations in 1998 [15], we know that neutrinos do indeed have mass. Further, given the tiny mass of neutrinos (which is much less than an electron volt of equivalent of energy, compared to the 511 keV mass of the electron and the 172 GeV mass of the top quark), scientists imagine that perhaps the mass of neutrinos arises not from interaction with the Higgs field like the other particles, but from some other sort of mechanism entirely. Clearly, understanding this one simple question (the origin of mass of neutrinos) is a crucial question as we attempt to develop a theory of everything.

Another big mystery not explained by the standard model is the observed asymmetry in matter and antimatter [16]. Antimatter is a complementary substance to ordinary matter. Combine the two and they release an enormous amount of energy. Conversely, you can convert energy into equal amounts of matter and antimatter. And that word "equal" is crucial. Since antimatter's discovery in 1931, we have learned a great deal about it and can make it at will. And whenever we have made matter and antimatter from energy, the amounts have been precisely identical.

This poses a problem when we combine this observation with our understanding of how the universe began. Using an enormous number of independent lines of evidence, we believe the universe began 13.7 billion years ago in a process called the Big Bang. Our universe was once much smaller, denser, hotter and dominated by energy. As the universe expanded and cooled, much of that energy converted into equal amounts of matter and antimatter. Yet everywhere we look in the universe, as far as our most powerful instruments can see, we see only matter. And that, as they say, is a problem. Where did the antimatter go? We know from looking at the cosmic microwave background (CMB) radiation and taking a census of the matter of the universe, that the number of energy particles outnumber the matter ones by a factor of about ten billion to one. From that, scientists have come to believe that a very slight asymmetry in the matter and antimatter of the early universe can explain the observations. This asymmetry paired 10,000,000,000 antimatter particles with 10,000,000,001 matter particles. The ten billion annihilated, forming the CMB, and leaving the sole matter particle to form the universe. And, of course, I am talking ratios here.

The origin of this asymmetry is not understood, although there are hints that the weak force may play a role. In 1964, scientists observed a slight asymmetry between matter and antimatter in the decay of neutral K mesons, which contain strange quarks. A confirming (and larger) asymmetry was observed in 2001 in the decays of neutral B mesons, which contain bottom quarks [17]. The behavior is tied together with the weak force's ability to change the identity of a particle. Consequently, scientists at the LHC are sifting through enormous numbers of events in which bottom quarks were created, looking for clues. In addition, physicists at Fermilab have constructed powerful beams of neutrinos and antineutrinos, hoping to compare the two to see if they act differently. If so, this could be the definitive evidence that leads to the evidence that explains the matter /antimatter asymmetry.

There is another enormous mystery in modern physics that is a bit subtler. This question revolves around the Higgs boson [18]. The mass of the Higgs boson is determined partially by the interaction of the Higgs boson with the Higgs field, but there is a complication. Due to quantum fluctuations, a Higgs boson can temporarily convert into pairs of fermions (top quarks and antimatter quarks) and bosons (W bosons, Z bosons, and even pairs of Higgs bosons). Because particles get their mass by coupling to the Higgs field, the Higgs boson plays favorites and preferentially fluctuates into heavier particles. The consequence of these quantum fluctuations is that they alter how one calculates the mass of the Higgs boson from first principles. These fluctuations add a term that is proportional to the maximum energy for which the standard model applies times the differences in the mass of the fermions and bosons. Since the maximum energy for which the standard model could apply is the Planck energy or about a quadrillion times higher than we can achieve with the LHC, that means that the mass of the fermions and bosons must be exquisitely tuned so as to cancel out this large energy. And we don't know why this must be. However, it provides another clue about a theory everything.

While we don't know the answer, a popular proposal is called supersymmetry [19], which postulates a symmetry between the fermions and bosons of the standard model. Each known fermion would have a companion boson and vice versa. And the Higgs boson could also fluctuate into the supersymmetric cousins. Since the contribution to the mass of the Higgs boson is related to the difference of the mass of the fermions and bosons, then having a supersymmetric cousin would naturally cancel out the effect of each of the ordinary matter particles. A special bonus of the idea of supersymmetry is that it can provide a candidate dark matter particle. Given that a theory of everything must answer all questions, the fact that a theory proposed to solve one mystery can solve another mystery is an attractive feature and explains, in part, why the theoretical community is so smitten by the idea.

Stumbling Forward

A theory of everything is an ambitious…indeed arrogant…endeavor. The idea that humanity can figure out a single and elegant theory that contains one or a few particles governed by a single force with an equation so simple it can be inscribed on a t-shirt, is truly a hopeful and optimistic goal. What ideas are out there?

Well I've mentioned superstrings. This theory has been popular. But it also has been unsuccessful at making testable predictions. On the theoretical level, not only are the solutions of superstring theory approximate, the equations themselves are also approximate. So we have a ways to go before we can hope for some success there.

Another idea is called loop quantum gravity (LQG) [20], which doesn't aspire to be a theory of everything, although it does hope to bring gravity into the quantum realm. LQG will finally explain what really happens at the center of a black hole and at the moment the universe began, by dispensing with the unphysical singularity and replacing it with a more sophisticated and accurate quantum treatment. One consequence of LQG is that it predicts at the smallest of scales…the Planck length (10^{-35} m) and Planck time (10^{-43} seconds), both space and time become quantized, leading to a smallest length and duration [21]. No theory of everything will be complete without an understanding if this conjecture is true.

And there are other proposals out there that space constraints do not permit me to describe here, like the idea that maybe the universe consists of more dimensions than the familiar three [22], or the possibility that our universe might be but one among many in a much larger and grander multiverse [23].

The quest for a theory of everything is a big dream…one of the biggest in all of science…but is one that is unlikely to be solved in our lifetime. To give a sense of historical perspective, Newton's first ideas unifying celestial and terrestrial gravity occurred in 1665, while Maxwell's unification of electricity and magnetism occurred two centuries later. And we have made huge strides in our understanding of the universe in the 350 years since Newton's first scribbled down his ideas, but the journey in front of us is incomparably larger still.

I think the core message is that this intellectual journey will not be a short one. Knowing God's Thoughts is a journey of the ages. Those of you reading this are unlikely to see the final product. But both you and your students can study the clues the universe leaves us and perhaps take us another step along the grandest scientific journey ever attempted.

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