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Article

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The Unification Paradigm in Theoretical Physics and the Beauty of God

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History provides numerous examples in which theoretical physicists have made progress in discovering new theories that provide more accurate descriptions of the physical world by intuitively relying on what is called here a unification paradigm. Some of the characteristics of this unification paradigm include an "unreasonable effectiveness" of the intimate linkage between advanced mathematics and the physical world, an ability to imagine a world of symmetrical states when the evidence at hand points to one of broken symmetries, a willingness to suspend our common sense and believe in phenomena that sit outside of normal experience, a deeply held sense of awe and wonder that comes from a focused study of the created world, and a profound sense that beauty reveals what is true. It is argued that the success of the unification paradigm is a manifestation of human efforts to grasp the beauty of God.

Keywords: theoretical physics, unification, mathematical beauty, God's beauty, faith integration

As far back as we can discern, humans have sought to understand the world. Explanations have generally involved some combination of natural and supernatural perspectives. For example, Feynman noted that at the time of Kepler, "one of the theories proposed was that the planets went around because behind them were invisible angels, beating their wings and driving the planets forward."[1] Feynman used this account to illustrate how planetary motion was understood at one time as the result of a mover (supernatural invisible angels) that was subsequently replaced by Newton's universal theory of gravitation in 1687 (which, as Feynman pointed out, is based on the concept of a gravitational force, the mediation of which is not fully explainable in physical terms).

It wasn't until Einstein's theory of general relativity in 1915 that the question of how gravitational fields influence the motion of objects in a local manner was provided. Through work undertaken in natural philosophy and then modern science, the remarkable success of our ability to describe natural phenomena in terms of physical theories has appeared to leave little room for a supernatural role in explaining the physical world around us.[2] Herein it is argued that an underlying principle that has contributed to the success of theoretical physics, what is called here the "unification paradigm,"[3] serves as a guidepost to the God of the Bible and thereby reinstates a supernatural underpinning for understanding the natural world.

The unification paradigm is rooted in a sense of awe and wonder that one can experience when considering the natural world, such as a feeling of perceiving God indirectly through a beautiful scene such as a magnificent sunset or the stunning display of the aurora borealis.[4] The beauty that is of interest in the current context is more subtle than these examples and is generally perceived only by those trained in advanced

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mathematics. In what follows, a selection of historical figures who made contributions to our understanding of the natural world by searching for theories that are mathematically "beautiful" is provided to make the case for the unification paradigm. That these historical figures span thousands of years puts the unification paradigm in a different category than typical Kuhnian scientific paradigms that are human constructs and that are prone to change from time-to-time. As such, it is argued that the underlying basis for the unification paradigm is God's eternal nature that is evident in creation.[5] This has implications for how to think about the relationship between the roles of faith and scientific reason in understanding the created world.

The Ancient World

Probably one of the earliest concepts that ultimately proved useful in providing a unifying framework was introduced in the 5th century BC when Greek philosophers proposed the concept of the "atom" as the smallest constituent of matter. Although it would take centuries before atomism's explanatory power would be realized,[6] it was a significant step that provided a means to understand a diverse array of physical phenomena in terms of the interactions of tiny indivisible particles. Also in the 5th century BC, the philosopher Empedocles advanced the idea that everything was made from at least one of the four elements: earth, water, air, and fire. Aristotle later added a fifth element, the aether (or ether), to explain the motion of the celestial bodies. In this manner, Aristotle promoted the view that all of nature could be described based on only five elements.[7]

These and many other contributions helped to lay a foundation for modern science as predicated on the view that disparate aspects of the physical world can be considered to be parts of a whole. Particularly noteworthy are the contributions of Archimedes (384–322 BC), who is generally remembered for discovering Archimedes' principle, that the buoyant force on an object in a fluid is equal to the weight of fluid displaced by the object.[8,9] Perhaps his most significant contribution was his recognition that mathematical models can be applied to the physical world.

One contribution from the Middle Ages that should be mentioned is William of Ockham's principle of parsimony, that the simplest explanations are most likely to be true. This principle, known as Ockham's razor, has provided valuable guidance in the unification paradigm. For example, parsimony provided a guiding heuristic in the principle of least action that played a foundational role in the Lagrangian and Hamiltonian formulations of modern theoretical physics. Albert Einstein's formulation of special relativity provides another example of the usage of Ockham's razor.

Scientific Revolution

During the Renaissance, much progress was made in the development of physical theories. Galileo Galilei rejected many of Aristotle's scientific explanations (e.g., that heavy objects fall faster than light objects) by conducting repeated experiments. He made significant contributions in mechanics, astronomy, engineering, and mathematics. In the words of Stephen Hawking, "Galileo, perhaps more than any other single person, was responsible for the birth of modern science."[10] Galileo put forward the invariance principle that the laws of motion are the same in all inertial frames of reference. This was an important precursor to Einstein's theory of relativity. The fact that Galileo preferred a simpler heliocentric model of the solar system, even though it didn't align well with the best empirical evidence at the time, is an early example of theoretical physicists who chose to promote a compelling theory due to its simplicity and beauty even though the theory disagreed with available experimental results.[11]

Classical Physics

In 1687, Isaac Newton published his landmark *Philosophiæ Naturalis Principia Mathematica (Principia)*, a three-volume work setting out his laws of motion and the law of universal gravitation.[12,13] The *Principia* provided the foundation for classical mechanics and was the first great step toward unification: it demonstrated that the motion of objects on Earth and the motion of celestial bodies in space can be described by the same theory. Indeed, the *Principia* provided a theoretical basis to derive the laws of planetary motion that Johannes Kepler had determined, based on the observations of Tycho Brahe. In this way, the moon's orbit around Earth is understood to be a result of the gravitational force of attraction.[14] Newton's work formed the dominant scientific viewpoint until the 20th century and played a significant role in the launch of the Enlightenment.[15] As F. J. Dyson states,

> … the very greatest scientists in each discipline are unifiers. This is especially true in Physics. Newton and Einstein were supreme unifiers. The great triumphs of Physics have been triumphs of unification.[16]

An additional contribution to classical mechanics that should be mentioned includes Joseph-Louis Lagrange's 1811 alternative formulation of mechanics, known today as Lagrangian mechanics.[17] This formalism enables one to determine the equation of motion of a system using energies (potential and kinetic) rather than forces as in Newtonian mechanics. In some cases, this makes analysis simpler and lends itself quite naturally to analyzing symmetries associated with a system. A powerful example of this is Noether's theorem,[18] which, in simple terms, says that if a physical system has a continuous symmetry property (e.g., if the Lagrangian is symmetric under rotations), then there are corresponding quantities that are conserved in time (for the above example, the angular momentum of the system would remain constant). Sir William Rowan Hamilton provided a reformulation of Langrangian mechanics in 1833, known as Hamiltonian mechanics. This formulation, that is also based on energies, uses the Hamiltonian function that proved to be useful in the development of quantum mechanics.

The next chapter in unification involved electricity, magnetism, and light. Approximately a century after the publication of the *Principia*, Charles de Coulomb determined that the force between two charged particles is proportional to the product of their charges and inversely proportional to the square of the distance between them—the same form of equation as Newton's law of gravitation.

In 1820, Hans Christian Ørsted reported that an electric current flowing through a wire produces a circular magnetic field around the wire. This suggested a linkage between electricity and magnetism and influenced Michael Faraday, who, despite having little formal education, became one of the greatest experimental scientists of all time. Faraday's discovery that a changing magnetic field passing through a coil produces a current in the coil was an important step in the unification of electricity and magnetism, as was his iron filing experiments with magnets, which led to his proposal of lines of force. To explain how electric and magnetic forces affect objects at a distance, Faraday proposed, in 1852, that electric and magnetic forces extend into empty space (rather than through a space-filling ambient ether).[19] Unfortunately, his proposal was not accepted by the scientific community until after his death. Faraday also demonstrated that magnetic fields could affect the polarization of light; this discovery suggested an underlying relationship between light and magnetic fields. Finally, Faraday demonstrated remarkable prescience[20] in his 1851 paper, "On the Possible Relation of Gravity to Electricity":

> Under the full persuasion that all the forces of nature are mutually dependent, and often, if not always, convertible more or less into each other, the author endeavoured to connect gravity and magnetic or electric action together by experimental results, and though the conclusions were, when cleared from all error, of a negative nature, he still thinks that the principle followed and the experiments themselves deserve to be recorded.[21]

While Faraday's mathematical abilities went only as far as basic algebra, the Scottish mathematician James Clerk Maxwell was well suited for the challenge of developing a mathematical model describing the relationship between electricity and magnetism. His 1855 presentation "On Faraday's lines of force" captured the current knowledge of electricity and magnetism in a set of twenty differential equations.[22] When published in 1861, his equations included a displacement current[23] in addition to the current that results from the flow of charges in a wire (that Ampère had used). The displacement current allowed Maxwell to derive the electromagnetic wave equation directly from his differential equations, with the implication that oscillating electric and magnetic fields in vacuum can interact with one another in such a manner as to form an electromagnetic wave.[24] Maxwell calculated the speed of the wave and found that it was approximately that of the speed of light. On this basis, he proposed that light is nothing other than an electromagnetic wave. Of Maxwell's achievement in showing that light was an electromagnetic phenomenon, Einstein wrote,

> The precise formulation of the time-space laws was the work of Maxwell. Imagine his feelings when the differential equations he had formulated proved to him that electromagnetic fields spread in the form of polarized waves, and at the speed of light! To few men in the world has such an experience been vouchsafed ... it took physicists some decades to grasp the full significance of Maxwell's discovery, so bold was the leap that his genius forced upon the conceptions of his fellow workers.[25]

Modern Physics

The advances in physics that were achieved by the end of the 19th century[26] laid the foundation for unification to drive theoretical physics in the 20th century. During the early 20th century, Albert Einstein united space, time, mass, and energy in his theory of special relativity (1905), and then spacetime with gravitation in his general theory of relativity (1915). It took the genius of Einstein to imagine a world outside of everyday experience, and by using thought experiments,[27] to determine equations that would apply at speeds close to the speed of light ($c \approx 300{,}000$ km/s) and in the presence of very strong gravitational fields. Einstein's work in relativity is the next step in the unification of the forces of nature.

An interesting dilemma existed between Newton's and Maxwell's great unifications: Newtonian mechanics requires the speed of light to depend on the reference frame of the observer[28] with respect to the light's source, whereas Maxwell's equations require the speed of light to be a constant (in technical terms, Maxwell's equations are not invariant under Galilean transformations).[29] Recognizing these challenges, Einstein postulated that light moves at a constant speed in a vacuum:

> Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relatively to the "light medium," suggests that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest … We will raise this conjecture (the purport of which will hereafter be called the "Principle of Relativity") to the status of a postulate, and also introduce another postulate, which is only apparently irreconcilable with the former, namely, that light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body.[30]

The consequences of these postulates are far reaching and include (amongst others[31]) the following.

- The Newtonian assumption that space and time are absolute no longer holds.[32]
- Space and time are interwoven in an inseparable four-dimensional continuum known as spacetime.
- No material object or information signal can travel faster than the speed of light in vacuum, ensuring that an effect cannot occur before its cause.

With a resolution to the electromagnetic wave/ether problem, Einstein generalized his special theory of relativity, with its preference of inertial motion (i.e., non-accelerating bodies) to incorporate more general motion (e.g., such as that associated with gravitational attraction). Special relativity requires that no information can travel faster than the speed of light, whereas Newton's theory of gravity depends only on the instantaneous spatial separation of two massive objects with no time-dependence in the equation or mechanism for mediating the gravitational attraction, a phenomenon referred to as "action at a distance."[33] A mechanism to mediate gravitational effects without exceeding the speed of light was needed. Einstein's theory of general relativity[34] used the fabric of spacetime as the mediator.[35] Just as Maxwell's equations give the electric and magnetic fields resulting from specified charges or currents, Einstein's field equations[36] describe the properties of the local spacetime manifold from energy and momentum specified in the form of what is called the energy momentum tensor.[37] Thus, general relativity tells us how matter causes the spacetime to curve, which, in turn, tells us how the motion of objects will follow the curvature of spacetime.[38]

Of Einstein's theory of general relativity, Paul Dirac said that it "was probably the greatest scientific discovery that was ever made."[39] Theoretical physicists speak of the "mathematical beauty" of Einstein's field equations. Dirac himself expressed the view:

> [Mathematical beauty] cannot be defined any more than beauty in art can be defined, but which people who study mathematics usually have no difficulty in appreciating.[40]

Notwithstanding Dirac's view, Subrahmanyan Chandrasekhar felt that it was possible to convey a sense of appreciation for the aesthetic appeal of general relativity:

> I shall … consider why a study of the general theory of relativity conduces in one a feeling not dissimilar to one's feelings after seeing a play of Shakespeare or hearing a symphony of Beethoven.[41]

A 2014 study[42] investigated the phenomenon described by Chandrasekhar. When fifteen mathematicians were asked to rate equations as either beautiful, neutral, or ugly, a brain scan showed that the same part of their brains activated (field A1 of the medial orbito-frontal cortex) as when people encounter visual or musical beauty. This suggests that there really is mathematical beauty akin to that of great art, or magnificent scenes in nature, or musical masterpieces.

Einstein's theory of general relativity has also played a significant role in the subsequent development of unification models in particle physics. The motion of planets, galaxies, clusters of galaxies, and the dynamics of the universe as a whole is primarily driven by gravitation. As such, general relativity provides a foundation for cosmology (the study of the universe on a large scale), as Einstein noted in his 1917 paper "Cosmological Considerations in the General Theory of Relativity."[43,44] In 1922, Alexander Friedmann calculated a solution[45] to Einstein's equations that corresponds to an expanding universe. Within five years, Georges Lemaître proposed that the observed recession of nearby galaxies would result if the universe were expanding, and in 1929, Edwin Hubble provided the first observational evidence that the universe is expanding uniformly in all directions. This led to the development of theories describing how the universe could have expanded from an initial state of extremely high density and temperature (what Fred Hoyle labelled the "big bang" in a BBC Radio broadcast in 1949). While there remains uncertainty about the details of this process, particularly in the first fraction of a second when the conditions lie outside our experimental capacity, big bang models have provided an explanation for phenomena such as the observed expansion of the universe, the abundance of light elements, the cosmic microwave background radiation, and the age of the oldest known stars. The physics of the early universe's rapid expansion shares a remarkable consonance with high energy particle physics. For example, the conditions during this phase are precisely those required for the electroweak symmetric state, where the fundamental forces of electromagnetism and the weak nuclear force unify. However, unresolved problems in the big bang model include the fine-tuning problem,[46] and the need to propose dark energy[47] and dark matter.[48]

Particle physics is based on the theory of quantum mechanics (QM) that was developed in the 20th century and that describes the properties of nature at the atomic and subatomic level. Characteristics of QM include quantities such as energy, momentum, and angular momentum (amongst others) that can take on only discrete values (hence the use of the term "quantum"); there is a limit to the precision to which certain pairs of particle properties (e.g., position and momentum) can be determined (this is known as Heisenberg's uncertainty principle); and quantum objects (e.g., electrons) sometimes display particle properties and sometimes wave properties (wave-particle duality). See Box 1 for a brief summary of key elements of QM.

Among the equations developed to account for the wave-like properties of matter, the Dirac equation combined classical electromagnetic theory, special relativity, and quantum mechanics, and was a significant step forward in the unification of particles and fields. At the time, particles (such as electrons) were viewed as permanent entities whereas quantum fields (such as photons) were considered to be excited states of the underlying quantized electromagnetic field. In the following few years, it was realized that even particles such as electrons could be viewed as excited states of quantum fields. This paved the way for quantum field theory (QFT), in which quantum electrodynamics (QED) is a particular example of QFT.

Efforts to unify the forces of nature in grand unified theories[49] (GUTs) involve particle physics, the study of fundamental particles, and their interactions. An important aspect of the unification model in particle physics was the recognition that there are specific symmetries associated with each of the electromagnetic, weak, and strong nuclear forces, and when the transformations that reflect those symmetries are required to be local (i.e., change from point to point in keeping with the principles of relativity), a unifying approach called "gauge theory"[56] results. For electromagnetism (the simplest gauge theory), the electric and magnetic fields can be represented by a 4-dimensional potential field. In this model, the quanta of the gauge field are bosonic exchange particles. Specifically, in QED the quanta of the gauge (electromagnetic) field are photons (i.e., they "mediate" the electromagnetic force between charged particles). Thus, recasting QED as a gauge

BOX 1: A Brief Primer on QM

1900: To explain the observed spectrum of radiation that disagreed with existing theories under certain conditions, Max Planck proposed that the energy, E, of a source of electromagnetic radiation can be emitted only in quanta (E = h, where h is Planck's constant—a fundamental constant in quantum mechanics—and is the frequency of the emitted electromagnetic radiation).

1905: Einstein explained the photoelectric effect, whereby shining light on certain materials resulted in emitted electrons only if the frequency of the light exceeded a certain threshold. Einstein[50] proposed that light consists of individual quantum particles (later called "photons"), which have energies given by Planck's quantum hypothesis.

1913: To explain the atomic spectrum of hydrogen, Niels Bohr published a model of the atom in which electrons orbit the nucleus in discrete fixed orbits (similar to the planets orbiting the sun), and so can change their orbital level only by absorbing or emitting discrete amounts of electromagnetic energy (in units of h).

1924: In his PhD dissertation, Louis de Broglie explained the discrete orbits of the Bohr model by hypothesizing that particles (e.g., electrons) can display wave properties. His prediction that the wavelength of a particle is inversely proportional to its momentum (with the constant of proportionality being Planck's constant) was experimentally verified[51] in 1927.

1925–1927: Mathematical formulations of "modern" quantum mechanics quantitatively account for the wave-like behavior of matter but represent phenomena that we cannot understand based on our everyday experience. Consequently, a number of "interpretations" of quantum mechanics have been proposed.[52]

1927: Paul Dirac[53] laid the foundations for quantum electrodynamics (QED) when he established a theory that successfully explained the emission and absorption of radiation by atoms by using first-order perturbation theory.[54] His theory partially unified quantum mechanics and special relativity but higher-order corrections were plagued with problematic infinities that weren't resolved until the mid-20th century.

1928: Paul Dirac developed the Dirac equation, a relativistic quantum wave equation for the electron.[55]

theory successfully predicted the quantum mechanical properties of the photon; however, it didn't, in and of itself, further the unification of forces. Nonetheless, it served as a prototype to consider the weak and strong nuclear forces.[57] In 1954, Chen-Ning Yang and Robert L. Mills[58] proposed a gauge theory of the strong nuclear force that predicted undiscovered massless charged mediating particles. Robert Crease and Charles Mann note,

> Yang and Mills could not understand why massless charged particles, if they existed, had not already been discovered. ("That was the embarrassment of it," Glashow says. "This lovely theoretical idea ended up predicting these massless charged particles that could not possibly exist!") Even though nature didn't seem to be cooperating, Yang and Mills thought that their idea was so beautiful that they went ahead and published it.[59]

As it turned out, their "beautiful" idea ultimately proved to be successful in describing the physical world, although it took the better part of two decades' work by multiple contributors, in the face of many nay-sayers, before a satisfactory theory of the unification of the electromagnetic and weak nuclear (electroweak) interactions was achieved.[60] Significant milestones in the development of gauge theory[61] are provided in Box 2.

Murray Gell-Mann and George Zweig's proposal of quarks as constituent particles formed the basis of quantum chromodynamics (QCD), the QFT of the strong nuclear force. Unlike QED where the mediating photons don't carry electric charge, the mediating particles in QCD, called "gluons," do carry the "color" charge of QCD of which there are three types. Subsequently, the theory of "asymptotic freedom" was proposed, that describes how the strong force does not get weaker with increasing distance beyond a limiting distance about the size of a baryon which enabled the formal development of QCD.

By the mid-1970s, this Standard Model of particle physics had become the dominant paradigm of the electromagnetic, weak, and strong nuclear forces. It accounted for known particles and their interactions (excluding gravitation) and predicted the properties of some new particles that were subsequently discovered, including the W and Z bosons (1983), the top quark (1995), the tau neutrino (2000), and the Higgs boson (2012). It has been shown experimentally that the electromagnetic and weak nuclear interactions function as a single electroweak force at very high energy. GUTs predict that, at an even higher energy, there would be only a single electronuclear interaction. By the 1970s, both QFT and general relativity made predictions that were confirmed by experiment to an accuracy that is equivalent to knowing the distance from New York to Los Angeles to within the thickness of a human hair. There was even some minimal progress on connecting quantum theory and gravitation with the introduction of black hole thermodynamics by Jacob Bekenstein[73] and Stephen Hawking.[74]

While unification models in particle physics have had many successes, there continue to be unresolved problems. One is the experimentally unconfirmed prediction of the decay of the proton, and there are some unresolved questions related to the Standard Model, such as why there is more matter than antimatter in the universe. Attempts to include the gravitational interaction into more elaborate models of particles such as string theory have not yet been fully successful.[75] In fact, advances based on the unification paradigm have arguably stalled. This may be an indication that

Box 2: A Brief Primer on Gauge Theory

1957: Julian Schwinger presented a gauge theory model of the weak nuclear force[62] (rather than the strong nuclear force) with the photon and two hypothetical vector bosons (W+ and W-) serving as the mediating particles.[63]

1961: Murray Gell-Mann and Sheldon Glashow observed that the special unitary groups studied by the French mathematician Élie-Joseph Cartan thirty years prior (denoted by SU[n]) had a remarkable correlation with the hypothetical virtual particles in gauge theories.[64] This was an important step in connecting mathematical beauty (as manifested in group theory) with physical reality (elementary particles).

1964: Guided by the properties of the group SU(3), Gell-Mann suggested that baryons (a set of "heavy" fermionic particles including protons and neutrons) and mesons (a set of "medium weight" unstable bosonic particles including pions and kaons) were composed of smaller particles he dubbed "quarks."[65] Quarks have fractional electric charge that come in multiples of one-third of the electric charge.[66]

1967: Steven Weinberg[67] and Abdus Salam[68] independently proposed that Glashow's W and Z particles get their mass through a phenomenon called spontaneous symmetry breaking.[69] In spontaneous symmetry breaking a field existing throughout space, called the "Higgs" field,[70] experiences a phase transition at extremely high energies (i.e., at a level associated with 10^{-12} s after the big bang).[71] A scalar particle predicted to exist at high energies by this theory, called the Higgs boson,[72] was detected at CERN's Large Hadron Collider near Geneva, Switzerland, in 2012.

current theories have not found the necessary element of mathematical beauty to unlock the next chapter in the unification journey.[76] Alternatively, there are some who hold the view that the idea of chasing after beautiful theories has outlived its usefulness and that the universe is actually too messy to continue to seek out beautiful theories to describe it.[77] Notwithstanding this criticism, herein it is argued that the search for beautiful theories is still warranted.

Mathematical Beauty

Amongst the many authors who have written about mathematical beauty,[78] one of the strongest proponents of pursuing mathematical beauty as a means to unlocking the secrets of the physical world was P. A. M. Dirac. In a paper entitled "Pretty Mathematics," Dirac wrote,

> A good deal of my research work in physics has consisted in not setting out to solve some particular problem, but simply examining mathematical quantities of a kind that physicists use and trying to fit them together in an interesting way regardless of any application that the work may have. It is simply a search for pretty mathematics. It may turn out later that the work does have an application. Then one has had good luck.[79]

This naturally raises the question, why is there such remarkable efficacy of the ideas that mathematicians formulate and their manifestation in the physical world? While some developments in mathematics were motivated by physical problems, such as Newton's formulation of calculus to describe the motion of objects more accurately, others were originally limited to the domain of pure mathematics and only much later found to have an application. For example, group theory, which had its origins in early 19th-century pure mathematics, was found to have multiple applications in physics and chemistry. Einstein formulated his theory of general relativity using the non-Euclidean Riemannian geometry[80] developed by Bernhard Riemann in 1854. There are numerous other examples in physics and other fields.[81]

In an article entitled "The Unreasonable Effectiveness of Mathematics in the Natural Sciences," Eugene Wigner observes that "the miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift which we neither understand nor deserve."[82]

From a Christian perspective, Alister McGrath offers the following:

> Sometimes abstract mathematical theories that were originally developed without any practical application in mind later turn out to be powerfully predictive physical models. Yet our familiarity with this fact has blunted our awareness that this is actually rather strange. For Polkinghorne, it was deeply puzzling that there was such a significant "congruence between our minds and the universe." Why does mathematics (a rationality we experience within ourselves) correspond so closely to the deep structures of the universe (a rationality observed beyond ourselves)? So what explanations might be offered for this strange observation? ... For many, the idea of God remains one of the simplest, most elegant, and most satisfying ways of seeing our world and understanding the place of mathematics within it.[83]

In his article entitled "Mathematics and Natural Theology," John Polkinghorne shares the following:

> Time and again it has proved to be a fertile technique of discovery in fundamental physics to seek theories that are formulated in terms of equations possessing the unmistakable character of mathematical beauty. This beauty is a rather rarefied form of aesthetic experience and, like most forms of beauty, it is easier to perceive than to describe. Nevertheless, it is a property whose presence the mathematicians are able to recognize and, significantly, to agree about … The physicists' quest for mathematical beauty is no mere aesthetic indulgence on their part, but a heuristic strategy that time and again has proved its worth in the four-century history of modern theoretical physics.[84]

A student of Dirac, Polkinghorne recalls that Dirac, "who was not a conventionally religious man, was once asked what was his fundamental belief. He strode to a blackboard and wrote that the laws of nature should be expressed in beautiful equations."[85]

When Ard Louis first encountered the Dirac equation (considered to be one of the most beautiful equations in physics) in an advanced quantum mechanics class, the equation that combined classical electromagnetism, special relativity, and quantum mechanics, and that predicted antimatter based on a new kind of symmetry in the laws of nature, he found Dirac's arguments "too fantastical to believe." Louis recounts,

> We may well ask: how does it happen that beauty in the exact sciences becomes recognizable even before it is understood in detail and before it can be rationally demonstrated? ... What I experienced was something closer to what philosophers have called the sublime. This is the sense of beauty mixed with terror that can occur when you for the first time see Mont Blanc or Mount Everest or experience a great sea-storm. I don't mean the kind of terror you feel when someone points a gun at you. Rather, it is the terror of your own finitude when confronted with something much bigger and greater than yourself. I felt like Dirac had given me an unauthorized glimpse of the transcendent; that I had gone where angels fear to tread.[86]

An important element of mathematical beauty is symmetry. Nature provides many examples of visible symmetry that instill a sense of beauty. Examples include snowflakes and sunflowers and the nautilus shell that displays a logarithmic spiral. In his book *Fearful Symmetry: The Search of Beauty in Modern Physics*, Anthony Zee discusses "the aesthetic motivations that animate twentieth-century physics." He states,

> The discovery of a symmetry is much more than the discovery of a specific phenomenon. A symmetry of spacetime, such as rotational invariance of Lorentz invariance, controls all of physics. We have seen that Lorentz invariance, born of electromagnetism, proceeds to revolutionize mechanics. And once the laws of motion of particles are revised, our conception of gravity has to be changed as well, since gravity moves particles.[87] … Today, symmetry considerations play the central role in the work of many fundamental physicists, myself included.[88]

Although the question of whether mathematics was invented or discovered has been debated since ancient times,[89] certainly a comprehensive description of the physical world requires a mix of mathematically beautiful theories and messy theories when those are the best one can do. Steven Weinberg notes the latter are needed to solve practical engineering problems while the former provide conceptual understanding:

> When the aim is not practical but conceptual, when you're trying to understand why we live in the kind of world we do, the kind of theory that is going to be useful to us would be a theory that has great mathematical beauty. Because it's only in that way that it could have explanatory power. If it's ugly, that means it has a lot of various discordant elements and you haven't really explained much because you have to say why is it that way, and not some other way. You haven't gotten very far. Whereas if it's beautiful, you have a feeling, ah, this explains it![90]

Theoretical physicists who discovered mathematical beauty in their descriptions of the universe have felt a deep sense of awe and wonder and even reverence. Shortly after his discovery of a matrix formulation of quantum mechanics, Heisenberg recalled a conversation he had with Einstein:

> If nature leads us to mathematical forms of great simplicity and beauty … we cannot help thinking that they are "true," that they reveal a genuine feature of nature … You must have felt this too: the almost frightening simplicity and wholeness of the relationships which nature suddenly spreads out before us and for which none of us was in the least prepared.[91]

On the matter of beauty, Einstein had this to say:

> The most beautiful and deepest experience a man can have is the sense of the mysterious. It is the underlying principle of religion as well as all serious endeavor in art and science. He who never had this experience seems to me, if not dead, then at least blind. To sense that behind anything that can be experienced there is something that our mind cannot grasp and whose beauty and sublimity reaches us only indirectly and as a feeble reflection, this is religiousness. In this sense I am religious. To me it suffices to wonder at these secrets and to attempt humbly to grasp with my mind a mere image of the lofty structure of all that is there.[92]

Is Unification Just a Kuhnian Scientific Paradigm?

The aesthetically guided motivation to understand nature has been in force from the time of the Greeks to the present. To appreciate just how remarkable this perennial feature of the unification paradigm is, it is necessary to consider the work of Thomas Kuhn, whose monograph *The Structure of Scientific Revolutions*[93] overturned the generally held view that progress in scientific knowledge was linear and continuous. Instead, Kuhn claimed scientific fields undergo episodic "paradigm shifts" in which "normal science," conducted within one distinct framework or paradigm of shared preconceptions, becomes increasingly plagued by discrepancies until a period of "revolutionary science" alters the paradigm. During this shift, "the scientist's perception of his environment must be re-educated—in some familiar situations he must learn to see a new gestalt."[94] Hence, science progresses through a sequence of paradigms, each characterized by a generally agreed-upon set of preconceptions that governs how the community of scientists will conduct their work until the next paradigm shift.[95]

Examples of revolutions in Kuhnian scientific paradigms referenced above include (1) the replacement of Aristotelian physics with heliocentric and classical mechanics in the Copernican and Newtonian revolutions, (2) the 19th-century replacement of caloric theories of heat with the modern laws of thermodynamics, (3) Maxwell's unification of formerly disparate ideas about electricity and magnetism, (4) the re-envisioning of matter, time, and motion in Einstein's special and general theories of relativity, (5) the replacement of classical mechanics with old quantum theory, (6) old quantum theory replaced with quantum mechanics, and (7) the unification of electromagnetic and strong and weak nuclear forces via quantum field theory. Notice that although several of these revolutions involved the unification of formerly disparate phenomena, the unification "paradigm" itself differs in several significant ways from these Kuhnian paradigms. Notably, the driving force behind the unification paradigm for many scientists is more of an intuitive instinct than a consciously held set of axioms. Further, it has persisted from the time of the Greeks to the present day.[96]

Herein it is proposed that, while Kuhnian scientific paradigms are human constructs and, as such, are prone to change, the unification paradigm is grounded in God's eternal nature evident in creation. Further, as Einstein noted, it is "something that our mind cannot grasp and whose beauty and sublimity reaches us only indirectly and as a feeble reflection."[97] This coheres with the Pauline understanding of general revelation in Romans, where Paul writes, "Ever since the creation of the world his eternal power and divine nature, invisible though they are, have been understood and seen through the things he has made" (Rom. 1:20a, NRSVA). It also agrees with ancient Hebrew conceptions of general revelation as expressed by the writer of Psalm 19, who proclaimed, "The heavens declare the glory of God; the skies proclaim the work of his hands" (Ps. 19:1, NIV).

This proposal, that mathematically beautiful unifying descriptions of nature declare the glory and divine nature of God, provides a plausible explanation of why people who have studied natural phenomena during the span of centuries and from within a vast array of societies with their own distinct shared values, beliefs, and cultures could be drawn to the unification paradigm. Nevertheless, many theoretical physicists who encounter mathematical forms of simplicity and beauty do not associate them with God. Georges Lemaître offers this perspective:

> Both … the scientist-believer and the scientist nonbeliever attempt at decoding the palimpsest of nature with multiple imbrications in which the traces of the various stages of the world's lengthy evolution has been overlapped and blended. The believer perhaps has an advantage of knowing that the riddle possesses an intelligent being, and consequently that the problem proposed by nature has been posed in order to be solved, therefore, that its degree of difficulty is presumably commeasurable with the present and future capacities of humanity.[98]

Historically, writers such as Irenaeus of Lyon, Anselm of Canterbury, Thomas Aquinas, John Calvin, Jonathan Edwards, Herman Bavinck, and Karl Barth have reflected on the divine beauty of God, although only some of these considered how the beauty of God might be revealed in nature.[99] While theologies of beauty received scant attention during the twentieth century,[100] Hans Urs von Balthasar inspired renewed theological interest in the topic of the beauty of God through his seminal *The Glory of the Lord: A Theological Aesthetics*.[101]

In the 21st century, a number of authors have contributed to the topic of a theology of beauty.[102] In particular, Jonathan King has provided a thorough biblical-theological analysis of the theology of beauty.[103] King frames his work as follows:

> My working hypothesis is twofold: first, beauty corresponds in some way to the attributes of God; second, the theodrama of God's eternal plan in creation, redemption, and consummation entails a consistent and fitting expression and outworking of this divine beauty. [104]

King does an excellent job of integrating the contributions of the historical figures mentioned above into his analysis of the question posed by Hans Balthasar:

> … may it not be that we have a real and inescapable obligation to prove the possibility of there being a genuine relationship between theological beauty and the beauty of the world?[105]

For King, God's beauty is an inherent aspect of his triune being, and the incarnation, death, and resurrection of Jesus display God's glory and beauty in redemptive history. He argues that an integrative approach of beauty, truth, and goodness enriches our understanding of God and his work.

McGrath also considered Balthasar's question in depth in *The Open Secret: A New Vision for Natural Theology*:

> An emphatic assertion of the beauty of the world and its theological importance is found in most writers of the patristic and medieval periods, who celebrated this beauty as something that is intrinsically delightful, while at the same time affirming its potential to lead those questing for a fuller disclosure of that beauty to discover its source and culmination in God.[106]

For McGrath, "the term 'natural theology' is now widely used to designate the intuition that there is some intellectual or imaginative connection between the natural world and a transcendent reality, such as God."[107]

In the words of Paul Ewart,

> Natural theology gathers from the world evidence for the existence of God and clues to his nature. In so doing it responds to a seemingly instinctive response that ascribes the beauty, power, and majesty of the universe to the work of a creator God. We sense that beyond the natural world lies a being that is not only responsible for its existence but gives it meaning and purpose.[108]

However, with the centrality of reason that characterized the Age of Enlightenment, McGrath points out that natural theology became conceived "solely in terms of the observed rationality of the natural order."[109] In his subsequent book *Re-Imagining Nature: The Promise of a Christian Natural Theology*, he offered a correction:

> A Christian natural theology celebrates and articulates the half-grasped rational transparency and oblique beauty of a complex and multifaceted nature, while at the same time proclaiming that a greater beauty lies beyond its horizon … A Christian natural theology is, in its own distinctive way, a theology of hope—a means of sustaining us as we travel through this sign-studded world, reassuring us that there is indeed a "big picture," which we presently grasp only in part.[110, 111]

The unification paradigm provides a fundamental connection, as viewed through the eyes of faith, between the glory of God and the mathematical beauty of those theories that best describe creation. In this regard, the unification paradigm could be viewed as an example of "a genuine relationship between theological beauty and the beauty of the world" as anticipated by Balthasar and, as such, provides an expression of faith integration.

The Unification Paradigm and the Lifelong Struggle to See Things Whole

One of the champions of the "integration of faith and learning," Arthur Holmes, referred to "faith integration" as "a lifelong struggle to see things whole, to think and become more consistently what we profess."[112] This "lifelong struggle to see things whole" is precisely the driving motivation of the unification paradigm. In turn, both the lifelong struggle and the unification paradigm cohere with the single triune God's revelation of himself through the complementary books of scripture and nature. So, it isn't a surprise that our instinct would be to adopt a unifying approach when searching for a deeper understanding of the mysteries of either the physical or theological realms. James Clerk Maxwell, one of the great unifiers in theoretical physics, viewed the study of nature as a means to strengthen human reason in God's service.

> Omnipotent God, who has created man in your image and has made him a living spirit so that he can seek and have power over your creatures, teach us to study the work of your hands in such a way that we can subject the earth to our use and strengthen our reason in your service, and receive your blessed word, so as to have faith in the one whom you have sent to give knowledge of salvation and the remission of our sins.[113]

Mark Noll similarly notes the importance of understanding the world for Christian discipleship when he describes Christ as "the Paradigm" and "the telos of all that is beautiful":

> Since the reality of Jesus Christ sustains the world and all that is in it, so too should the reality of Jesus Christ sustain the most whole-hearted, unabashed, and unembarrassed efforts to understand the world and all that is in it. The Light of the World, the Word of God, the Son of Man, the True Vine, the Bread of Life, the Bright and Morning Star—for believers, this One is the Savior, but also the Paradigm … The light of Christ illuminates the laboratory, his speech is the fount of communication, he makes possible the study of humans in all their interactions, he is the source of all life, he provides the wherewithal for every achievement of human civilization, he is the telos of all that is beautiful. He is, among his many other titles, the Christ of the Academic Road.[114]

The proposal offered here is that creation contains guideposts[115] that enable us to discover theories that are truer than their alternatives, with one example of such a guidepost being the unification paradigm that points fundamental physical theories to the beauty of God. From the vantage point of Christian natural theology, the pursuit of such theories is Christocentric and part of the Christian calling to reflect the beauty of God.

In conclusion, the unification paradigm illuminates the profound relationship between theoretical physics and the transcendent beauty of God. This paradigm, that is rooted in the mathematical elegance that has guided centuries of scientific discovery, invites us to see scientific endeavor not merely as the pursuit of knowledge of the physical world but also as a journey toward a deeper understanding of God's divine beauty. Critics may argue that the association between mathematical beauty and divine nature is misplaced. Yet, as Einstein observed, the beauty and sublimity of the natural world point beyond themselves to something mysterious and awe-inspiring. Christianity provides a compelling explanation: God's eternal power and divine nature are revealed through the things he has made.

The unification paradigm challenges us, as Holmes noted, to undertake "a lifelong struggle to see things whole."[116] The mathematical beauty that undergirds theoretical physics is not an end in itself but a guidepost to the ultimate source of all beauty—the God of creation. As such, the steady reduction in emphasis on the supernatural in science comes full circle, resulting in fundamental theoretical descriptions of the physical world that reflect God's eternal beauty and so point to God.

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Notes

[1]Richard P. Feynman, Robert B. Leighton, and Matthew Sands, *The Feynman Lectures on Physics,* New Millennium Edition, Volume I (Basic Books, 2010), 142, https://dunapress.com/wp-content/uploads/2020/04/The_Feynman_Lectures_on_Physics_-_VOL1.pdf.

[2]Many Christians who contributed to the foundation of modern science saw its laws as expressions of a manifestation of God's wisdom in creation. In this regard, see Peter Harrison, "Laws of God or Laws of Nature? Natural Order in the Early Modern Period," in Peter Harrison and Jon Roberts, ed., *Science Without God? Rethinking the History of Scientific Naturalism* (Oxford University Press, 2019), 17–35.

[3]"Unification" is used extensively in the literature, and Thomas Kuhn introduced the term "paradigm" in science in his important publication, Thomas S. Kuhn, *The Structure of Scientific Revolutions* (University of Chicago Press, 1962). The combined label "unification paradigm" is not commonly used.

[4]See, for example, Ryan West and Adam C. Pelser, "Perceiving God Through Natural Beauty," *Faith and Philosophy* 32, no. 3 (July 2015): 293–312.

[5]The author is indebted to the editor-in-chief of *Perspectives on Science and Christian Faith* for bringing to his attention the article by Tracee Hackel that proposes beauty as a common dialect of physics and Trinitarian theology. Hackel notes the work of John Philoponus, an ancient Christian natural philosopher, who anticipated the unification word of Faraday and Maxwell. Tracee Hackel, "Physics and Christian Theology: Beauty, a Common Dialect?," *In Pursuit of Truth: A Journal of Christian Scholarship* (October 31, 2007), https://www.cslewis.org/journal/physics-and-christian-theology-beauty-a-common-dialect/2/. The editor-in-chief also provided helpful references to Thomas F. Torrance, *Theological and Natural Science* (Wipf and Stock, 2002) and Ernst Peter Fischer, *Beauty and the Beast: The Aesthetic Moment in Science,* trans. Elizabeth Oehlkers (Plenum Trade, 1997).

[6]See J. R. Milton, "The Limitations of Ancient Atomism," in *Science and Mathematics in Ancient Greek Culture*, ed. Christopher Tuplin and T. E. Rihll (Oxford University Press, 2002): 178–95.

[7]While many of Aristotle's scientific proposals ultimately proved to be wrong, they were revered for many centuries until the 13th-century condemnations of Paris explicitly rejected dogmatic interpretations of Aristotelian physics.

[8]Legend has it that the king was suspicious that the goldsmith who made a crown for him had mixed in some silver, so he consulted with Archimedes, the cleverest person in the city. Archimedes, while taking a bath, noticed the displacement of the water when he got into the tub and had a revelation about how to calculate the density of the material making up the crown. The story is that he was so excited that he ran into the street naked shouting "Eureka!" or "I have found it!" Whether or not Archimedes coined the term "Eureka" in this way, it does represent the moment of inspiration that is a common thread through the journey of discovery of modern physics.

[9]In fact, it has only been since 1999 that the real depth of the contributions of Archimedes have come to light: See Reviel Netz and William Noel, *The Archimedes Codex: Revealing the Secrets of the World's Greatest Palimpsest* (Da Capo Press, 2007).

[10]Stephen Hawking, *A Brief History of Time* (Bantam Books, 1988), 179.

[11]David C. Lindberg, "Galileo, the Church, and the Cosmos," in *When Science and Christianity Meet,* ed. David C. Lindberg and Ronald L. Numbers (University of Chicago Press, 2003), 33–60.

[12]Having recently experienced the COVID-19 pandemic, it is interesting that

> Even on entry to Trinity College, Cambridge, [Newton] did not stand out until, ironically, the University was forced to close during 1665 and 1666 due to the high risk of plague. Newton returned to Woolsthorpe and began two years of remarkable contemplation on the laws of nature and mathematics which would transform the history of human knowledge. (Jon Balchin, *Quantum Leaps: 100 Scientists Who Changed the World* [Arcturus, 2006], 66)

[13]Newton's three laws of motion describe the relationship between the motion of an object and the forces acting on it. The law of universal gravitation states that every particle attracts every other particle with a force that is proportional to the product of their masses and inversely proportional to the square of the distance between them.

[14]If the moon didn't have a velocity in the direction of its elliptical orbit, it would fall directly to the earth. Likewise, if the force of gravity didn't exist, the moon would move in a straight line past the earth (Newton's first law of motion). However, because the moon does have a velocity (its average orbital speed is about 1 km/s) *and* there is a force of gravitational attraction between the moon and the earth, the moon is continually "falling" toward the earth as it progresses along its elliptical orbit.

[15]In addition to his contributions in classical mechanics, Newton made significant contributions in optics and shares credit with Gottfried Wilhelm Leibniz for the development of infinitesimal calculus. Newton proposed a corpuscular (particle) theory of light which opposed a wave theory of light that Christiaan Huygens had introduced several decades earlier. This dual understanding of the nature of light would prove to play an important role in quantum mechanics.

[16]Freeman J. Dyson, *Infinite in All Directions* (Harper, 1985), 45.

[17]Joseph-Louis Lagrange, *Mécanique Analytique* (Ve Courcier, 1811).

[18]Emmy Noether, "Invariante Variationsprobleme," *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse* (1918): 235–57.

[19]Michael Faraday, "Experimental Researches in Electricity. —Twenty-Ninth Series. On the Physical Character of the Lines of Magnetic Force," *Philosophical Magazine* (June 1852): 407–37.

[20]Faraday's exploration of a potential link between gravitation and electromagnetism foreshadowed 20th-century efforts.

[21]Michael Faraday, "Experimental Researches in Electricity. Twenty-Fourth Series. On the Possible Relation of Gravity to Electricity," *Abstracts of the Papers Communicated to the Royal Society of London* 5 (1851): 994–95, http://doi.org/10.1098/rspl.1843.0267.

[22]A differential equation is a mathematical equation that relates one or more unknown functions and their derivatives.

[23]The displacement current arises when an electric field changes with respect to time. This can occur not only in some materials, but also in vacuum.

[24]James Clerk Maxwell, "A Dynamical Theory of the Electromagnetic Field," *Philosophical Transactions of the Royal Society of London* 155 (1865): 459–512.

[25]Albert Einstein, "Considerations Concerning the Fundaments of Theoretical Physics," *Science* 91, no. 2369 (May 24, 1940): 487–92.

[26]One additional step of unification in the 19th century took place in thermodynamics when heat was connected to the kinetic theory of gases.

[27]In German, *Gedankenexperiment*.

[28]In special relativity, Einstein recognized that the results of measurements of variables such as distance or speed always need to refer to the coordinate system or reference frame from which they are being measured, to be meaningful.

[29]It was generally believed that a medium permeating all space (referred to as the luminiferous aether) was required in order for an electromagnetic wave to propagate say from the sun to the earth. It was believed that the ether would provide an "absolute" reference frame from which all speeds could be measured. However, the careful experiments conducted by Albert A. Michelson and Edward W. Morley in 1887 yielded a "null" result (meaning that there was no evidence of an ether).

[30]Albert Einstein, "Zur Elektrodynamik bewegter Körper," *Annalen der Physik* 17 (1905): 891–921; English translation "On the Electrodynamics of Moving Bodies," in H. A. Lorentz, A. Einstein, H. Minkowski, and H. Weyl, *The Principle of Relativity,* trans. W. Perrett and G. B. Jeffery (Dover, 1952), 37–38.

[31]Other consequences of special relativity include the following:

- Two spatially separated events (e.g., two flashes of light) that occur simultaneously for one observer won't occur simultaneously as measured by another observer if the observers are moving relative to one another;
- The interval of time measured between two events won't be the same for two observers if they are moving relative to one another (this is referred to as "time dilation");
- The measured length of an object won't be the same for two observers if they are moving relative to one another in the direction of the object being measured (this is referred to as "length contraction");
- The mass of an object as measured by an observer depends on the velocity of the object relative to the observer; and
- Mass and energy are equivalent according to the well-known equation $E = mc^2$ (where E is the energy of a particle, m is its mass, and c^2 is the square of the speed of light).

[32]The corrections to Newton's equations are significant for velocities that approach the speed of light and are important in modern particle physics experiments.

[33]In the *Feynman Lectures* noted above, Feynman joked that Newton's "force" could be thought of as "invisible angels" that "fly in a different direction" (p. 142) since there is no physical explanation of how the force is mediated between the two objects.

[34]Albert Einstein, "Die Feldgleichungen der Gravitation," *Königlich Preußische Akademie der Wissenschaften* (Berlin). *Sitzungsberichte* 25 (1915): 844–47; English translation, "The Field Equations of Gravitation," in *The Collected Papers of Albert Einstein, Volume 6: The Berlin Years: Writings, 1914–1917,* trans. Alfred Engel (Princeton University Press, 1997), 117–20, https://einsteinpapers.press.princeton.edu/vol6-doc/272.

[35]In 2017, Rainer Weiss, Kip Thorne, and Barry Barish received the Nobel Prize in Physics for their role in the direct detection of gravitational waves that were generated by the merger of two black holes that propagated as ripples in spacetime at the speed of light. Black holes were predicted by general relativity as the remnant of a massive star after it collapses.

[36]Einstein's gravitational field equations are second order nonlinear partial differential equations that can only be solved exactly by making simplifying assumptions.

[37]The curved manifold of general relativity is represented in differential geometry by a pseudo-Riemannian metric. In the limit of zero curvature, one recovers that flat Minkowski spacetime of special relativity.

[38]One of the confirmations of Einstein's theory is that light from the sun bends as it grazes the moon's surface during a solar eclipse as a consequence of following the curvature of spacetime.

[39]Subrahmanyan Chandrasekhar, "The General Theory of Relativity: Why 'It Is Probably the Most Beautiful of All Existing Theories,'" *Journal of Astrophysics and Astronomy* 5 (1984): 3–11, https://doi.org/10.1007/BF02714967.

[40]Chandrasekhar, "The General Theory of Relativity," 5.

[41]Chandrasekhar, "The General Theory of Relativity," 5.

[42]Semir Zeki, John Paul Romaya, Dionigi M. T. Benincasa, and Michael F. Atiyah, "The Experience of Mathematical Beauty and Its Neural Correlates," *Frontiers in Human Neuroscience* 8 (2014): 68, https://doi.org/10.3389/fnhum.2014.00068.

[43]Albert Einstein, "Kosmolgische Betrachtungen zur allgemeinen Relativitätstheorie," *Königlich Preußische Akademie der Wissenschaften* (Berlin). *Sitzungsberichte* (1917): 142–52; English translation "Cosmological Considerations in the General Theory of Relativity," in *The Collected Papers of Albert Einstein, Volume 6: The Berlin Years: Writings (1914–1917)*, 540–52, https://einsteinpapers.press.princeton.edu/vol6-doc/568.

[44]The prevailing view at the time was that the universe was static and unchanging. Einstein's calculation showed that the field equations did not yield a result consistent with this view, so he inserted an additional term in 1917 (subsequently called the cosmological constant) as a repulsive force to balance the gravitational attraction of the matter of the universe. It was later reported that Einstein considered the insertion of the cosmological constant to be the "biggest blunder" of his life (for a recent account, see Cormac O'Raifeartaigh, "Investigating the Legend of Einstein's 'Biggest Blunder,'" *Physics Today* 30 [October 30, 2018], https://doi.org/10.1063/PT.6.3.20181030a).

[45]Assuming that the universe in general is homogeneous and isotropic.

[46]For example, if the density of matter and energy in the universe were only slightly higher than it is (about one part in 10^{62}), then matter would have collapsed on itself before the conditions were right for us to exist, and if it were only slightly lower, no galaxies or stars would have formed.

[47]The fact that observation shows that the expansion of the universe is accelerating (one would expect the expansion of normal matter to decelerate under the influence of gravitation) has suggested that about 68% of the energy, dubbed "dark energy" in the universe has a negative pressure. Some have proposed that the cosmological constant could be used to represent dark energy.

[48]Astronomical observations have shown that there doesn't appear to be sufficient (normal) matter to explain the motion of galaxies. In fact, it is currently believed that about 85% of matter is "dark," i.e., that it interacts neither with the electromagnetic field (so it doesn't emit radiation) nor with normal "baryonic" matter.

[49]A grand unified theory (GUT) is any model in particle physics that merges the electromagnetic, weak, and strong forces (the three gauge interactions of the Standard Model) into a single force at high energies. Although this unified force has not been directly observed, many GUT models theorize its existence. See Robert P. Crease and Charles C. Mann, *The Second Creation: Makers of the Revolution in Twentieth-Century Physics* (MacMillan, 1986) for a helpful historical account of the Standard Model.

[50]Einstein was awarded the 1921 Nobel Prize for the discovery of the law of the photoelectric effect. He did not receive a Nobel Prize for his work in relativity.

[51]In the words of Richard Feynman:

> Newton thought that light was made up of particles, but then it was discovered, as we have seen here, that it behaves like a wave. Later, however (in the beginning of the twentieth century) it was found that light did indeed sometimes behave like a particle. Historically, the electron, for example, was thought to behave like a particle, and then it was found that in many respects it behaved like a wave. So it really behaves like neither. Now we have given up. We say: "It is like neither." …
>
> Because atomic behavior is so unlike ordinary experience, it is very difficult to get used to and it appears peculiar and mysterious to everyone, both to the novice and to the experienced physicist. Even the experts do not understand it the way they would like to, and it is perfectly reasonable that they should not, because all of direct, human experience and of human intuition applies to large objects. We know how large objects will act, but things on a small scale just do not act that way. So we have to learn about them in a sort of abstract or imaginative fashion and not by connection with our direct experience. (Richard P. Feynman, Robert B. Leighton, and Matthew Sands, *The Feynman Lectures on Physics,* New Millennium Edition, Volume III [Basic Books, 2010], 655)

[52]In the most popular interpretation, advanced by Niels Bohr and Werner Heisenberg and called the Copenhagen interpretation, it is argued that one can achieve only a probabilistic description of nature at the very small scale (e.g., one can calculate the probability that an electron will be detected at a certain location, but it is not possible to know the path it followed to get to that location). As well, if a quantum system can exist in more than one state, then it will remain in a "superposition" of those states until an observation of the system is made and the superposition "collapses" into one or another of the possible states. In order to emphasize how strange this aspect of the Copenhagen interpretation is, Erwin Schrödinger illustrated this property in terms of macroscopic objects—his famous Schrödinger cat thought experiment. Imagine a cat is put into a sealed box with a flask of poison and a radioactive source in such a configuration that if a Geiger counter detects radioactivity (say, with a 50% chance), a mechanism causes the flask to shatter, releasing the poison and killing the cat. The Copenhagen interpretation requires that the cat be simultaneously alive *and* dead (the two states that it can take on) until someone looks into the box (makes an observation), at which point the cat is *either* alive *or* dead. Einstein disliked the idea of a probabilistic interpretation and, in 1935, Albert Einstein, Boris Podolsky, and Nathan Rosen (EPR) published a paper, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" (*Physical Review* 47 [May 15, 1935]: 777–80, https://cds.cern.ch/record/405662/files/Physrev.47.777.pdf), in which they argued that, while quantum mechanics is correct as a theory, it is *incomplete*. A "complete" theory would require "hidden variables." Einstein refused to accept that nature might demonstrate what he called "spooky actions at a distance" or violations of local realism. In 1964, John Bell questioned whether there were any real objection against a completely realistic account of all quantum phenomena or not. His quest led him to the famous Bell inequality that recast the EPR argument into quantitative terms, opening the way for an empirical comparison between the predictions of quantum mechanics and local realism. The most definitive experimental results that followed were achieved in 1982 by Alain Aspect et al., violating Bell's inequality and clearly supporting the *nonlocal* predictions of quantum mechanics.

[53]Paul A. M. Dirac, "The Quantum Theory of the Emission and Absorption of Radiation," *Proceedings of the Royal Society of London* A 114, no. 767 (March 1927): 243–65, https://doi.org/10.1098/rspa.1927.0039.

[54]In quantum mechanics, perturbation theory is an approach whereby one develops an approximate solution for a complex system by using a known solution for a simpler system and then progressively solves for corrective terms in a series.

[55]Paul A. M. Dirac, "The Quantum Theory of the Electron," *Proceedings of the Royal Society of London* A 117, no. 778 (February 1928): 610–24, https://mathweb.ucsd.edu/~nwallach/Dirac1928.pdf.

[56]In 1919, Hermann Weyl proposed that electromagnetism might be invariant under a local change of length scale or "gauge" (a term borrowed from railroads in reference to the different distances between the tracks). At the time, Weyl's proposal didn't appear to have merit, and the term "gauge" was subsequently associated with a change of the phase of the quantum mechanical wave function. Since then, several authors have proposed models based on Weyl's scale invariance, including the current author who proposed a geometric model using microscopic wormholes to explain the nonlocal behavior at the microscopic scale (W. R. Wood and G. Papini, "A Geometric Formulation of the Causal Interpretation of Quantum Mechanics," *Foundations of Physics Letters* 6, no. 3 [1993]: 207–23).

[57]The strong nuclear force is an attractive force between particles like protons and neutrons that keeps the nucleus together. The weak nuclear force is responsible for the radioactive decay of certain nuclei. Both nuclear forces act over a short range. The strong nuclear force is about 100 times stronger than the electromagnetic force and 10,000 times stronger than the weak nuclear force.

[58]C. N. Yang and R. L. Mills, "Conservation of Isotopic Spin and Isotopic Gauge Invariance," *Physical Review* 96 (1954): 191–95, http://dx.doi.org/10.1103/PhysRev.96.191.

[59]Robert P. Crease and Charles C. Mann, "How the Universe Works," *The Atlantic Monthly* (August 1984): 74, https://

www.theatlantic.com/magazine/archive/1984/08/how-the-universe-works/666820/.

60The 1979 Nobel Prize in Physics was awarded to Sheldon Glashow, Abdus Salam, and Steven Weinberg for their contributions in establishing the electroweak theory.

61See Crease and Mann, "How the Universe Works," for an engaging narrative of this chronology in honor of Sheldon L. Glashow.

62Julian Schwinger, "A Theory of the Fundamental Interactions," *Annals of Physics* 2, no. 5 (1957): 407–34.

63Sheldon Glashow subsequently suggested that there should be *four* virtual particles (the photon, W^+, W^-, and Z) rather than three, and he made the connection between the special unitary group SU(2) x U(1) and the electromagnetic and weak nuclear interaction. Sheldon Glashow, "Partial-Symmetries of Weak Interactions," *Nuclear Physics* 22, no. 4 (1961): 579–88.

64Murray Gell-Mann and Sheldon Glashow, "Gauge Theories of Vector Particles," *Annals of Physics* 15 (1961): 437–60.

65Murray Gell-Mann, "A Schematic Model of Baryons and Mesons," *Physics Letters* 8, no. 3 (1964): 214–15. George Zweig proposed a similar model (with constituents called "aces") also in 1964 in George Zweig, "An SU(3) Model for Strong Interaction Symmetry and Its Breaking," CERN Report No. 8182/TH.401, http://cds.cern.ch/record/352337/files/CERN-TH-401.pdf. Initially, quarks were considered to be nothing more than a useful classification device. However, in 1968, the physical existence of quarks was demonstrated in deep inelastic scattering experiments at the Stanford Linear Accelerator Center.

66Baryons are made up of three quarks (or anti-quarks) in such a manner that the resultant electric charge is always an integer and the spin is a half-integer, whereas mesons are made up of a quark and an anti-quark with integer electric charge and integer spin and are extremely short-lived. Quarks are bound by the strong nuclear force within baryons and mesons, whereas leptons (the lightest matter constituents such as the electron and neutrino) experience only the weak nuclear force. Glashow proposed that there might be a fourth quark that he called "charm," in addition to the "up," "down," and "strange" quarks. See B. J. Bjørken and S. L. Glashow, "Elementary Particles and SU(4)," *Physics Letters* 11, no. 3 (1964): 255–57. Even though Glashow and Bjørken had no justification for a fourth quark, they went ahead and published the idea anyway. Once again, their intuition based largely on aesthetics, paid off. The current model includes two additional (much heavier) quarks: top and bottom (some physicists used the terms "truth" and "beauty" for a period of time).

67Steven Weinberg, "A Model of Leptons," *Physical Review Letters* 19 (1967): 1264–66.

68Abdus Salam, "Weak and Electromagnetic Interactions," in *Proceedings of the 8th Nobel Symposium*, ed. N. Svartholm (Almqvist and Wiksell, 1968): 367–77.

69The idea of spontaneous symmetry breaking and the role that the resulting "Goldstone" bosons might play in both condensed matter physics and particle physics had been studied by researchers such as Yoichiro Nambu and Philip Anderson in the early 1960s.

70Named after Peter Higgs, one of the scholars working in this area.

71During a phase transition (e.g., the freezing of water), the state of matter changes as well as the symmetry associated with the phase of the matter. A higher degree of symmetry occurs at higher temperatures, whereas at lower temperatures, the symmetry is "broken." Prior to the phase transition of the Higgs field in the very early universe, there would have been a single electroweak interaction with all the mediating particles being massless. After the phase transition, the W and Z particles acquired mass (which causes the weak nuclear interaction to be short ranged) and the electromagnetic and weak nuclear interactions became decoupled.

72See The ATLAS Collaboration, "A Detailed Map of Higgs Boson Interactions by the ATLAS Experiment Ten Years After the Discovery," *Nature* 607 (2022): 52–59, https://doi.org/10.1038/s41586-022-04893-w.

73J. D. Bekenstein, "Black Holes and the Second Law," *Lettere al Nuovo Cimento* 4, no. 15 (1972): 737–40.

74S. W. Hawking, "Black Hole Explosions?," *Nature* 248 (1974): 30–31.

75It should be noted that the principle of supersymmetry was introduced in the mid-1970s to try to address some of the gaps left by the standard model and has continued to play an influential role in unification approaches since then. Supersymmetry proposes that forces and matter should be treated on an equal footing. To accomplish this, a "superpartner" is hypothesized for all known particles, fermions, and bosons. If supersymmetry exists in nature, these new particles should be detectable at facilities such as the Large Hadron Collider (LHC), but no positive results have been obtained to date. Indeed, LHC data suggest that supersymmetry requires some fine-tuning, which was one of the factors that it was designed to get rid of. See Lee Smolin, *The Trouble with Physics: The Rise of String Theory, the Fall of Science, and What Comes Next* (Houghton Mifflin, 2006) and Joseph Lykken and Maria Spiropulu, "Supersymmetry and the Crisis in Physics," *Scientific American* 310, no. 5 (May 2014): 34–39, for overviews of supersymmetry and related theories. Another challenge is that current experimental capabilities are insufficient to provide confirmation of some of the proposed models such as loop gravity, asymptotic safety, and non-commutative geometry.

76A promising candidate is Weyl conformal invariance that some authors have proposed existed in the very early universe with the fixed standards of length that Einstein argued exist, emerging as a result of conformal symmetry breaking. See C. Condeescu, D. M. Ghilencea, and A. Micu, "Weyl Quadratic Gravity as a Gauge Theory and Non-metricity vs. Torsion Duality," *The European Physical Journal C* 84 (2024): article 292, https://doi.org/10.1140/epjc/s10052-024-12644-6 and references therein for a recent argument for the advantages that Weyl gravity provides with regard to addressing challenges on the SM.

77See, for example, Sabine Hossenfelder, *Lost in Math: How Beauty Leads Physics Astray* (Basic Books, 2018).

78See, for example, S. Chandrasekhar, *Truth and Beauty: Aesthetics and Motivations in Science* (The University of Chicago Press, 1987); Frank Wilczek, *A Beautiful Question: Finding Nature's Deep Design* (Penguin Press, 2015); Hunkoog Jho, "Beautiful Physics: Re-Vision of Aesthetic Features of Science Through the Literature Review," *Journal of the Korean Physical Society* 73, no. 4 (August 2018): 401–13; Ivan Melo, "Aesthetic Criteria in Fundamental Physics—The Viewpoint of Plato," *Philosophies* 7 (2022): 96–111, https://doi.org/10.3390/philosophies7050096; and Ivan Melo, "The Role of Beauty in Physics," *Communications—Scientific Letters of the University of Zilina* 20, no. 1A (2018): 144–48, https://doi.org/10.26552/com.C.2018.1A.144-148. See Russell Howell, "Beauty," in *Mathematics Through the Eyes of Faith,* ed. James Bradley and Russell Howell (HarperOne, 2011), chap. 7, for a comprehensive analysis of mathematical beauty from a Christian perspective.

[79]P. A. M. Dirac, "Pretty Mathematics," *International Journal of Theoretical Physics* 21, no. 8/9 (1982): 603–5.

[80]In Riemannian geometry, parallel lines can converge or diverge.

[81]For example, see Peter Rowlett, "The Unplanned Impact of Mathematics," *Nature* 475 (2011): 166–69, https://doi.org/10.1038/475166a.

[82]Eugene Wigner, "The Unreasonable Effectiveness of Mathematics in the Natural Sciences," *Communications on Pure and Applied Mathematics* 13, no. 1 (February 1960), 157, https://onlinelibrary.wiley.com/doi/10.1002/cpa.3160130102.

[83]Alister E. McGrath, *Science and Religion: A New Introduction,* 3rd edition (Wiley-Blackwell, 2020), 197–99.

[84]John Polkinghorne, "Mathematics and Natural Theology," in *The Oxford Handbook of Natural Theology,* ed. Russell Re Manning, John Hedley Brooke, and Fraser Watts (Oxford University Press, 2013), 449.

[85]John Polkinghorne, *Belief in God in an Age of Science* (Yale University Press, 2003), 2.

[86]Ard Louis, "Beauty and the Sublime in Physics," *Theos* (February 2, 2023), https://www.theosthinktank.co.uk/comment/2023/02/02/beauty-and-the-sublime-in-physics.

[87]Anthony Zee, *Fearful Symmetry* (Macmillan, 1986), 73–74.

[88]Zee, *Fearful Symmetry*, 99.

[89]Among physicists, Wigner advocated for the point of view that mathematics is real and discovered by people. Einstein considered it to be a product of human thought. There are compelling arguments on both sides. Others argue that there is room within mathematics for both universal truths as well as human constructs. See, e.g., Harold Heie, "Developing a Christian Perspective on the Nature of Mathematics," in *Teaching as an Act of Faith,* ed. Arlin C. Migliazzo (Fordham University Press, 2002), 95–116. The author is indebted to Professor Heie for the faith-integration mentoring that he provided as part of a CCCU new faculty workshop 30 years ago.

[90]See the online interview of Steven Weinberg by Ali Kaya entitled "Is Mathematics Invented or Discovered?," https://abakcus.com/video/steven-weinberg-is-mathematics-invented-or-discovered/ (January 10, 2020), 6:55–7:52. Note that the Lawrence Livermore National Laboratory announced that it had successfully sparked a fusion reaction that released more energy than went into it just two months after Weinberg's interview.

[91]Chandrasekhar, "The General Theory of Relativity," 4.

[92]Marco Bersanelli and Mario Gargantini, *From Galileo to Gell-Mann: The Wonder That Inspired the Greatest Scientists of All Time,* trans. by John Bowden (Templeton Press, 2009), 7.

[93]Thomas S. Kuhn, *The Structure of Scientific Revolutions,* 2nd edition (University of Chicago Press, 1970).

[94]Kuhn, *The Structure of Scientific Revolutions,* 112.

[95]One practical way that this can play out is in the determination of what research grants will be approved.

[96]In this regard, the unification "paradigm" might more aptly be called the unification "meta-paradigm" since it has persisted from one scientific paradigm to another.

[97]Einstein, in Bersanelli and Gargantini, *From Galileo to Gell-Mann,* 7.

[98]Lemaître, in Bersanelli and Gargantini, *From Galileo to Gell-Mann,* 244.

[99]Indeed, Barth famously said "Nein!" (No!) to Natural Theology.

[100]Laura Smit, "Review Essay: The Theology of Beauty," *Calvin Theological Journal* 57, no. 1 (April 2022): 143–49.

[101]Hans Urs von Balthasar wrote a sixteen-volume theological "trilogy" on the good, the true, and the beautiful.

[102]For other recent contributions, see, for example, Jeremy Begbie, ed., *Sounding the Depths: Theology Through the Arts* (SCM Press, 2002); Jo Ann Davidson, *Toward a Theology of Beauty: A Biblical Perspective* (University Press of America, 2008); David de Bruyn, "Jonathan Edwards's Synthesis of Definitions of Beauty," *Artistic Theologian* 8 (2020): 75–98; and Junius Johnson, *The Father of Lights: A Theology of Beauty* (Baker Academic, 2020). A recent contribution in science that contains a discussion of theological beauty is Grace Lew, "Teaching the Beauty of God in Computer Programming and Design," *Perspectives on Science and Christian Faith* 73, no. 4 (2021): 220–27, https://www.asa3.org/ASA/PSCF/2021/PSCF12-21Lew.pdf.

[103]Jonathan King, *The Beauty of the Lord: Theology as Aesthetics* (Lexham Press, 2018).

[104]King, *The Beauty of the Lord*, 23.

[105]Hans Urs von Balthasar, *The Glory of the Lord: A Theological Aesthetics,* Volume 1, trans. Erasmo Leiva-Merikakis (T&T Clark, 1998), 80.

[106]Alister E. McGrath, *The Open Secret: A New Vision for Natural Theology* (Blackwell, 2008), 262.

[107]Alister E. McGrath, "Natural Theology," in *St Andrews Encyclopaedia of Theology*, ed. Brendan N. Wolfe et al. (2022), https://www.saet.ac.uk/Christianity/NaturalTheology.

[108]Paul Ewart, "The Physical Sciences and Natural Theology," in *The Oxford Handbook of Natural Theology,* ed. Russell Re Manning, John Hedley Brooke, and Fraser Watts (Oxford University Press, 2013), 421.

[109]McGrath, *The Open Secret,* 268.

[110]Alister E. McGrath, *Re-Imagining Nature: The Promise of a Christian Natural Theology* (Wiley-Blackwell, 2016), 183.

[111]Jason Wilson has drawn upon Alister McGrath's work on truth, beauty, and goodness in his article, "Integration of Faith and Mathematics from the Perspective of Truth, Beauty, and Goodness," *Perspectives on Science and Christian Faith* 67, no. 2 (2015): 100–110, https://www.asa3.org/ASA/PSCF/2015/PSCF6-15Wilson.pdf.

[112]Arthur F. Holmes, "The Closing of the American Mind and the Opening of the Christian Mind: Liberal Learning, Great Texts, and the Christian College," in *Faithful Learning and the Christian Scholarly Vocation,* ed. Douglas V. Henry and Bob R. Agee (Eerdmans, 2003), 112.

[113]Bersanelli and Gargantini, *From Galileo to Gell-Mann,* 250.

[114]Mark A. Noll, *Jesus Christ and the Life of the Mind* (Eerdmans, 2011), 22.

[115]Perhaps there are other guideposts such as God's truth and goodness that would be useful to scholars in seeking theories with more permanence. An indication that one has encountered such a guidepost could be the sense that "they reveal a genuine feature of nature" (Heisenberg), or that "there is something that our mind cannot grasp and whose beauty and sublimity reaches us only indirectly and as a feeble reflection" (Einstein), or that feeling of "eureka!" (Archimedes).

[116]Holmes, "The Closing of the American Mind and the Opening of the Christian Mind," in *Faithful Learning and the Christian Scholarly Vocation*, ed. Henry and Agee, 112.