Science, Irrationality, & Innovation
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S. James Gates, Jr. is a theoretical physicist specializing in string theory at the University of Maryland College Park. Gates is well known as one of the earliest workers in the field that would later become known as string theory first coming across ideas of supersymmetry during his graduate work at MIT in the 1970s. He later contributed to the first comprehensive volume on supersymmetry, "Superspace: or, one thousand and one lessons in supersymmetry." In this article for the Kean Review, he talks about how irrationality versus pure reason often has a huge impact on the creative process and popularity of theories in science.

While I use the word "science" in my title, in fact my essay is really only about innovation in the part of theoretical physics about which I have some intimate knowledge and well founded opinions. Facts are the necessary basis of opinions, and by concentrating on this small part of science that I know best, I hope to illustrate some points applicable to science in general [1].

In the following essay, I will attempt to do three things by way of commenting on what I have seen of the process of scientific innovation at work. The first task is to provide a working definition of science. In the second part of this essay, I try to explain my understanding of the boundary of theoretical science, the place where research innovation takes place. While established science is governed by the rigorous use of mathematics and logic, I believe the boundary of science is quite a different place. It is a bit untamed. Logic and rigor still count for a lot. However, surprisingly a type of "irrationality" seems present as the fundamental enabling element that permits scientific knowledge to expand. In the final part of this essay, I turn my commentary on the efforts, as I have viewed them, to establish a mathematically complete paradigm for superstring/M-theory.

Presently science, though its application to technology, has been remaking the rules by which the wealth of nations will be determined in the future. The

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principal agencies of this are the Internet and World Wide Web. Resulting from new developments in science such as "nano-science" and "genomic-based science," we appear to be living at the dawning of an age where the technological application of science will potentially have the ability to remake the meaning of the word "human." There is both great promise and peril in this.

Science - An error-correcting meme

The evolutionary biologist Richard Dawkins defined the term "meme" to represent a unit of cultural knowledge that in many ways demonstrates behavior that is remarkably similar to a gene [2]. By this definition, science qualifies as a meme. However, it is a very special sort of meme that I wish to spend some time to define. I argue that science is an error-correcting meme. That is, science acts to correct errors in the collective human understanding of the physical reality of which it is a part and to expand the breadth of this understanding.

While the use of logical rationality is a hallmark of science, there is what I think of as an "irrational" basis for science. The mathematician Kurt Gödel (1906-1978) essentially showed the impossibility to formulate a completely axiomatic system. Simply put, making working assumptions as a basis for deriving subsequent statements is unavoidable, and these assumptions precede and ultimately lie outside of the system of rational scientific analysis. In order to begin the work of science, I believe we must accept two propositions. First, that there are attributes of the universe whose properties and dynamical evolution are governed by rational laws that are independent of the consciousness of the observer. Secondly, we must assume that human consciousness is capable of discerning these and able to represent them in some form of human language.

All I have to say assumes these fundamental articles of faith, fundamental propositions, that allow for science, as we know it, to exist. Scientific culture promotes a rationalist reality-based view of the objective universe. This view of our universe, our working hypothesis, has been the chief enabler of scientific and technological progress over the last few centuries.

The field of physics has been deeply influenced by many great intellectuals. Galileo Galilei (1564-1642) "pushed" a particular way to view the world by use of a very specialized language—mathematics. Mathematics had been used well prior to Galileo in descriptions of the physical world (a discovery we can ascribe to Pythagoras (582-502 BCE)), but Galileo's studies of motion, trajectories, and rates of change led to a fundamental increase in the mathematical basis of the physical sciences. Galileo described Natural Philosophy, the intellectual and immediate predecessor to physics, in the following way:

Natural Philosophy is written in the great book which ever lies before our eyes—I mean the universe but we cannot understand it if we do not first learn the language in which it is written. The book is written in the mathematical language and the symbols are triangles, circles, and other geometrical figures, without whose help it is impossible to comprehend a single word of it; one wanders in vain through a dark labyrinth [3]

Following after Galileo, Isaac Newton (1643-1727) solved the problem of motion with the invention of "the Calculus." This proved a fundamental breakthrough in the development of physics and all of the physical sciences. It is also interesting to note that the mathematician Gottfried Leibniz (1646-1716) at about the same time made this same leap. Even more interesting is recent evidence calculus may have been created by Archimedes (287-212 BCE) but lost to humanity until the work of Leibniz and Newton.

Humanists may be surprised to think of mathematics as a language, but this is a part of life for physicists. Mathematics is, in fact, a very interesting and strange language with many properties in common with other languages. I tell nonscientists to think about mathematics as a language because this is the way scientists make use of it. I also have described mathematics as an organ of perception. By this I mean theoretical physicists are working to gain insight into structures that make up levels of existence to which we have no direct access. We achieve this first by the means of mathematics. We "see" these levels first with mathematics.

An illustration of this process can be seen in the ability to detect atoms. Using present day technology in the form of "atomic force microscopes," individual atoms can be directly imaged. This has only become possible within the last decade. Yet in a very real way, physicists have been "seeing" atoms for about one hundred years. We can trace this especially back to one of the great works of Einstein in 1905. That year he wrote "On the Movement of Small Particles Suspended in Stationary Liquids Required by the Molecular Kinetic Theory of Heat," published on July 18, 1905.

This work of Einstein firmly established the existence of atoms and their size. Thus, we physicists have "seen" atoms by way of their mathematical description in theories that explain observable behavior in our world. For us, mathematics really is another means for viewing the universe. I often tell young people mathematics is an extrasensory perception organ. Of course, I am not the first person to notice this very strange property of mathematics. Charles Darwin (1809-1882) once said, "Mathematics seems to endow one with something like a new sense." For one who uses mathematics this way, if often seems to function like a "third eye of science." [4]

Even for those of us who make use of the tool of mathematics in physics, or science in general, it has a lot of surprising properties. One of these properties I refer to as "telepathy." All languages have the power to convey ideas from one mind to another. To this extent, the telepathic power of languages is ubiquitous. However, the precision of the transmittal of concepts using mathematics is striking when compared to other forms of human communication.

A property of the mathematical language is that if an object or idea has a mathematical description, there is automatically a way to communicate it in a precise and detailed way to the minds of others. This is true even though the others have no previous experience with the new discovery and even if there is no substantial experiential commonality between the members communicating. The mathematically precise understanding of the discovery is accessible to anyone with a sufficiency of mathematical "numeracy" (the analog of literacy). This is one reason why it is so often seen in science fiction writing that humans first communicate with putative aliens via the use of mathematics. Humanity's experience with mathematics suggests that it is a universal language for rational discourse about physical reality. Mathematics has this peculiar telepathic nature to it because of the precision it enforces in its users. In a very real way we can know with much more precision than with other forms of human communication what another person is thinking. This precision does not exist in the media of aural, written, graphical, or visual representations outside of mathematics. In mathematics, we share a common platform for the exchange of concepts.

Often nonscientists appear subject to an illusion that science uncovers truths for our species. This is not the work of science. It reveals theories about the structure of the universe. Albert Einstein once said,

> *It is difficult to attach a precise meaning to the term scientific "truth." Thus, the meaning of the word "truth" varies according to whether we deal with a fact of experience, a mathematical proposition, or a scientific theory.* [5]

While other fields of human thought are said to present truths, science only reveals theories. The use of the word theory recognizes that any paradigmatic explanation of facts (i.e. scientific observation) is a proposition that can be proven false. Any claim made to being a part of science must surrender *ab initio* to this property, and it must in principle allow (by the action and reasoning of scientists) for the claim to be proven false. I sometimes say, "Science is not actually about finding the truth. It is about making our beliefs about our home—the universe—less false."

Scientists are aware that ours is a clever species. Due to our cleverness, science must take into account we are also clever enough to fool ourselves. Accordingly, built into the structure of science there are mechanisms for error correction. This is the role of what has been called the scientific method and the means by which we discern arguments, observations, and experiments that provide a basis for our system of beliefs. Modern science most directly gained this as a legacy from Galileo. Einstein said of this circumstance,

> *Propositions arrived at by purely logical means are completely empty as regards reality. Because Galileo saw this, and particularly because he drummed it into the scientific world, he is the father of modern physics—indeed of modern science altogether.* [6]

A corollary to such a system is that scientists must be willing, when presented with a preponderance of evidence, to abandon beliefs previously held as correct. In science, there can be no ultimate certainty about one's scientific beliefs. Part of the charge to each new generation of scientists is to check and recheck the "canon" of this system of belief that is its inheritance from previous generations.

Among systems of belief, science is almost unique in this embrace of fallibility and limitations on human ability and perception. Instead of a weakness, this is the source of the strength of science. It can be argued this unremitting dedication to the refinement of our understanding of the universe gives science, through its application in technology, more power to alter the quality of human life than perhaps any other system of belief. Certainly human history over the course of the last several centuries supports this.

Science lies at the intersection of several different and not completely overlapping regions. One of these is the realm of human imagination, and mathematics is part of this. A second realm consists of physical reality, and the final realm is a subset of this that corresponds to that part in which the technical competence of our species permits it to observe and manipulate portions of physical reality. Science, as we know it, can only exist in the region where these three completely overlap. Not all are static. It is clear that what we call technological progress means that the technical competence of our species is expanding. The part of the circle of physical reality that lies outside of our technical competence and mathematical imaginations constitutes the realm of profoundly unknown parts of physical reality.

It is possible to observe phenomena without possessing the requisite mathematical ideas to explain and give complete context to the observations. An example is the phenomenon of "high temperature" superconductivity, for which there exists no accepted scientific theory. Perhaps the opposite example to this is the part of physics known as superstring/M-theory. Here we have lots of mathematical imagination, but no observational basis of this set of ideas. It remains a piece of "prephysics," "protophysics," or "putative physics." Some of its detractors even say that it is "metaphysics," i.e., not physics.

Science - At the Irrational Boundary of Theoretical Physics

Knowledge (mathematical, scientific, and technological) is finite. It possesses a boundary beyond which we are blind. The only human facility by which we go beyond this boundary is imagination. A theoretical physicist is essentially a mathematician who has the ability to calculate something useful about our cosmos. We imagine new answers and solutions. We make them up! However, as scientists we are charged with taking this marvelous facility and seeking nature's confirmation that we are less incorrect than with our previous theories. Einstein's comment was that it was the sad fate of most theories to be shown incorrect shortly after their conception. For those not so roughly treated, at most nature says, "Maybe." Again and again we go to the laboratory to see if the new paradigm gains support. Many times at the blackboard, I have told students, "Physics is not about what I write on the board. It is about what happens in the laboratory."

Science is thus always in a state of "tentativity" (if I may introduce such a term), a state mostly static but with punctuating dynamic periods of changes in scientific theories about the universe. This culture must accept that its most cherished theories at some point in the future will likely be changed. Such shifts from one theory to another are dramatic and vividly illustrate Einstein's dictum: "Imagination is more important than knowledge." [7] Geology has shown us that life on our planet has repeatedly had to face the challenge of mass extinctions, often apparently caused by violent shifts in the earth's environment. During these extinctions, large numbers of species come to the end of their existence. Something similar occurs in theoretical physics.

The "Newtonian/Bohr-Schrödinger-Heisenberg Extinction" illustrates such a boundary. Prior to this "event" (lasting approximately from 1905-1926), it was possible to argue that many different ideas might hold the explanation for why the puzzle of atomic spectra occurred in nature. At the conclusion of this period of transition, one such theory emerged in the community of theoretical physicists as the consensus answer…quantum theory. Quantum theory is considerably more mathematically sophisticated than its ancestor paradigm, classical Newtonian physics. As in evolutionary biology, the extinction yields a concept that is more complicated than what went before. Quantum theory is not derivable from classical Newtonian theory; it is a daring leap of the imagination beyond it. This history suggests that in theoretical physics, the creation of a genuinely new rational paradigm is itself an irrational process.

While I argue that here we can see "irrationality" once again emerge in a surprising way in the scientific enterprise and that appearance has large implications for governing the rate and pace of innovation, there is in this history another important point to note. Scientific belief is the product of consensus within a community bound together by a common set of shared values. This reliance on consensus is both a strength and a hindrance. Unlike in a democracy, not all scientists are created equal. This means the progress of the community is particularly influenced by the role of individuals that appear in its history. This fact explains why it is often the case that the use of a few names seem at first capable of assignment as the reason scientific progress occurs. The reality is that scientific progress is often, far more than generally realized, the result of an enormous amount of information exchanged between disparate thinkers around the world.

The process of developing new scientific knowledge is a difficult task, as is all innovation. Some ideas are more fruitful to follow as working propositions than others. However, at any given time in the marketplace of ideas, it is not at all clear which in fact are most fruitful for future progress. This means that any researcher in this environment faces making a decision about which ideas to pursue. A difficulty lies in the fact that whatever choice is made involves a commitment usually of enormous amounts of resources (time, effort, etc.) on the basis of a severe lack of relevant information. In this situation, one strategy is to trust the intuition of other scientists with a record of past achievement. This confers enormous power to any scientist chosen to play this role. In an area of research that is in a state of flux, it is often the case that a conventional wisdom arises. On the other hand, this strategy also lessens the number of approaches that are either attempted or even proposed for how to make progress. Thus, this strategy also has the very great possibility of stifling innovation. The theoretical physics community is faced somewhat with a Hobbesian choice…maximize efficiency or maximize region of exploration. Maintaining a healthy balance is the challenge that is constant. In this circumstance, decisions are made based only on intuition, guesses, etc. In other words, I argue that once again "irrationality" becomes a factor in the operation of an entire scientific community.

This aspect of "irrationality" also throws light onto other curious and often overlooked factors that can emerge. One of these I believe can be characterized as “style.” When I discuss this with other theoretical physicists, the first reaction can be one of puzzlement: “What is the meaning of style in theoretical physics or mathematics?” Sometimes an initial reaction is, “Certainly no such thing exists in mathematics.”

Anyone, I believe, who reads primary source literature in mathematics over a sufficiently long period of time can quickly conclude that there was a very different style to the writing and thinking about mathematics just over one hundred years ago. Some might argue that we have come to a sort of end of history and have advanced to the point that style in mathematical thinking will undergo no additional evolution. In my opinion this is unlikely. One reason for this is the rapidly increasing capabilities of computers.

Thus far throughout the history of our species, there has been essentially a single route to the mastery of mathematics. One had to first master the symbolic language used to express mathematical ideas. This is so ubiquitous that it is easy to lose sight of the fact that the symbolic representation of mathematical ideas is separate from the ideas. To understand this point, I have a favorite analogy. There is another area of human accomplishment that contains both a powerful, even universally accepted intellectual construct as well as a powerful symbolic way of representing ideas. This is the example of music. Music exists through the widely accessible experience of listening, but it also exists in the form of written scores. The latter mode of transmitting musical ideas is limited only to people who read music. The reason for the wide access to music by listening is due to the existence of a myriad of instruments, from the human larynx to woodwinds, strings, percussion devices, etc., for playing it.

To my thinking, computers are on their way to becoming to mathematics what orchestral instruments are to music. The ultimate application of computers in mathematics may not be a matter of simply computation. I believe it is possible that with sufficient time, computers may become the engines for CEC, computer-enabled-conceptualization. Using my analogy, the computer could perhaps permit a genius to explore realms of mathematics even though that person has never mastered the standard symbolic representations of mathematics that have been our tradition for millennia. Should this development occur, it would greatly increase the percentage of humanity that engages in the study of mathematics. Just as musical geniuses who do not read scores exist, there may arise mathematical geniuses who do not master traditional mathematical symbology. Without the difficulties of the usual approach to expressing mathematical ideas, it seems most likely that at least a new patois for mathematics might develop.

I argue that if the mathematical language upon which so much of the structure of theoretical physics rests and has played a substantial role in shaping its culture can be subject to changes in style, then so too can the field itself. This in turn will likely have an implication for the ultimate success of investigations in theoretical physics. Style seems likely linked to the sorts of irrational choices that are made. If this is the case, then style has indeed an important implication. Different styles of music exist and enrich the engagement and interaction humanity has with it. We are certainly not impoverished by the fact that musicians pursue different styles of the art form. As a working physicist, I believe I can perceive different national styles in the endeavors of theoretical physicists. These are very subtle, but I believe they make a major contribution to the vitality of the field.

The allowance to believe that such differences in style might exist explained for me what was a long-standing puzzling statement I heard many years ago made by Nobel Laureate Abdus Salam [8]. He suspected that when a sufficient number of people of the African diaspora started to engage in theoretical physics, something like jazz would appear. It was fifteen or twenty years before I had the intimate knowledge of theoretical physics necessary to interpret this statement well enough to understand his meaning. I believe he was talking about the idea of style of which I have been discussing. A concomitant notion is that this is why diversity matters. To maximize the breadth of investigations, the greatest intellectual diversity would seem a prudent condition to support.

Superstring/M-Theory

In the ordinary course of progress in theoretical physics, the process whereby "irrationality" plays a role is kept in check by the ever-present demand that whatever mathematical structure is under discussion should have as a metric its success and capability to describe observational data. In my own area of research that touches on superstring/M-theory, there is currently a popular debate underway on this point.

While I personally do not agree with the essential thrusts of the two separate works by Smolin and Woit [9] (eds. note: both of these authors have written books severely criticizing string theory and its methodologies.), I believe it is illustrative to examine a few examples of the actual struggle underway to complete the purely mathematical understanding of this still emerging topic. Note I have emphasized the word "mathematical." Even if a conceptually complete version of superstring/M-theory exists, does it provide an accurate mathematical description of the physics of our cosmos?

Due to the mathematically incomplete nature of the current development of superstring/M-theory, there exist enormous possibilities for putative results as part of the conventional wisdom. One of the most widely accepted parts of the conventional wisdom about superstring/M-theory is that it predicts hidden dimensions. Using this as a lens, I wish to spend some time discussing how nature may not possess such hidden dimensions and yet might still be described by some version of superstring/M-theory.

Prior to Einstein, the scientific establishment believed that light was similar to all other waves. As all other waves move in a medium, it was thought there must exist a medium in which light waves propagate. This medium was called the "luminiferous aether" or "ether" for short. All efforts to detect the ether have failed even to this day. Like the ether, the idea of quarks—for a period of the history of theoretical physics—was one that had no critical observational support. To this day, no direct isolation of quarks has been made. Yet today, quarks are an accepted part of scientific lore. So why was one set of ideas about the unseen accepted and the other rejected? The answer is, of course, that though direct isolation of quarks has never been achieved, the indirect evidence for their existence is overwhelming. So in the history of theoretical physics these examples show that sometimes ideas must be given a provisional acceptance in order to find evidence to support the idea. This example allows us to wonder if the putative extra hidden dimensions in superstring/M-theory are ether-like (to eventually disappear) or quark-like (to eventually be supported by indirect evidence).

In our universe, the mathematical description of photons, particles of light, is provided by a set of functions called "the 4-potential." Photons are related to measureable electric and magnetic forces. However and most remarkably, photons described by different 4-potentials can nonetheless lead to exactly the same measurable electric and magnetic forces! Two photons described by two such 4-potentials are called "gauge equivalent." However, since the two 4-potentials are really distinct, there must be some way to tell them apart. There is. Shortly after the description of such 4-potentials was discovered, physicists realized that there was a mathematical quantity given the name "the gauge parameter." In the nineteen thirties, a physicist named Nicholas Kemmer (1911-1998) found the surprising result that the gauge parameters act like angles that one measures with a protractor, even if there are no hidden dimensions present!

By the end of the nineteen eighties, a remarkably complete mathematical description of the physics required to describe the universe at the level of subatomic particles had been completed. It is called the standard model. It not only constitutes a mathematically complete paradigm, it is the most rigorously tested piece of scientific theory that has ever existed in the history of our species [10]. It literally agrees with thousands and even tens of thousands of experimental observations. It is an impressive achievement not only in terms of the sheer number of experiments with which it agrees, but also in terms of the precision of some of these tests. One such test is called the "gee minus two" experiment.

The type of structure containing only the usual three dimensions of space, one dimension of time and multiple numbers of Kemmer angles is the fundamental mathematical backbone of the highly successful standard model. Mathematicians call this structure a "fiber bundle." In much of the current discussion of superstring/M-theory, one finds the statement that the mathematical self-consistency of the constructs requires hidden dimensions. If this were strictly so, experiments ruling out extra dimensions would also rule out the possibility of that superstring/M-theory can describe our universe. It turns out, however, that this point—due to the lack of a mathematically complete formulation of superstring/M-theory—possesses a loophole. This loophole, as far as I can tell, is logically consistent and yet it has not become part of the conventional wisdom.

In my own work during the late eighties, completed in conjunction with W. Siegel [11], evidence was presented that the approach of Kemmer could be directly implemented in superstring/M-theory. The evidence supported the idea that no hidden dimensions are required for the mathematical consistency of superstring/M-theory. Readers not intimately familiar with the topic might be tempted to regard this as a recent breakthrough. This is not so; our work was completed in 1989.

My work with Siegel suggested direct connections to Kemmer angles and fiber bundles are consistent with the idea of superstring/M-theory without hidden dimensions. Throughout the middle to late eighties, several groups of physicists tackled the idea that perhaps string theory could describe a four-dimensional approach such as the type known to occur as the mathematical foundation of the standard model. Using an approach called "free fermions," one group of theorists extensively investigated such possibilities. In a different approach another collaboration used a technique called the "covariant lattice" to reach the same result [12]. Thus there were three different approaches to the formulation of superstring/M-theory without the inclusion of hidden dimensions and my work with Siegel was not unique in this regard. The unique feature of our work was the direct connection to Kemmer angles. I should perhaps mention that the presence of Kemmer angles in these models does not rule out hidden dimensions [13]. In fact, the first work completed with Siegel provided a description of conventional ten-dimensional string theory.

Someone outside the field might be tempted to ask why if these results were found didn't more physicists pay attention to them? This is a question that has many answers. First, all superstring/M-theory constructions that only contain the usual three dimensions of space, one dimension of time, and multiple numbers of Kemmer angles are significantly more complicated mathematically than the ones that contain hidden dimensions. Although there was no mathematical reason not to explore these alternative four-dimensional versions of superstring/M-theory, the majority of the community felt these were "inelegant" and lacked of a certain sense of beauty. I have long held that Nature is the only arbiter on this matter or as Einstein said, "If you are out to describe the truth, leave elegance to the tailor." [14] This is an example of one of the irrational choices to which I alluded in the previous chapter. In the absence of compelling evidence otherwise, the consensus by which the community makes progress went against these constructions.

More recently, with the motivation provided by the observational data that our cosmos seems to be presently in a phase of accelerated expansion, a number of physicists investigating superstring/M-theory have begun to look anew at these "inelegant" constructions under the guise of what is called "the landscape." [15] In the absence of a complete mathematical paradigm, such phase transitions in the conventional wisdom of superstring/M-theory are all but guaranteed to occur.

It is my belief that there are hints to suggest superstring/M-theory can become "ordinary" theoretical physics. To see some of this, a reconsideration of the standard model is a good example. To build the standard model, there are choices that must be made in order for it to be consistent with observational results. In fact, the standard model is only one of an infinite collection of mathematically consistent constructions called quantum relativistic field theories or field theories for short. In order to use the field theory to describe our world, there are approximately twenty numbers that must be fixed to get the physics correct. In addition to these numbers, choices have also have to be made about the Kemmer angles as well as the number of basic constituents of matter. These constituents are called quarks and leptons. Among the twenty or so numbers to be fixed are their masses. Thus field theory constitutes what I have called a lathe for physics. One definition of a lathe describes it as "a machine capable of remarkable precision and versatility, but requiring a skilled and experienced operator for its success." A lathe confers upon its user the power to make choices.

While it has been the conventional wisdom for most of the history of superstring/M-theory that the presence of such choices in this area are not to be viewed favorably, my work with Siegel showed evidence of precisely such properties. In these works, choices could be made about the number and properties of the Kemmer angles. Similarly, choices could be made about structures that seemed to control the number of constituents.

In 1989 during a series of lectures in Poland, I made the following remark

> *This present situation is extremely unsatisfactory and leaves enormous room for speculation on the behavior of string theories. For example, one such problem concerns "the four dimensional vacua" of strings theories. Presently, it is widely believed that a unique vacuum for heterotic string theory should be chosen by the dynamics. I like to think of this as the "Ptolemaic view" of string theory. The belief in a unique vacuum is akin to a belief in a unique place for the earth in earlier cosmology. The alternate "Copernican view" is more to my liking. After all, why should only one vacuum be consistent? In general relativity, the next most complicated gauge theory, the vacuum is not determined by the theory. Until a nonperturbative understanding of strings is achieved, this question will remain unanswerable.* [16]

My remark refers to the irrational choices my intuition led me to believe would be important for progress in the field. In particular, the attribute of an infinity of mathematically consistent solutions was an expression of my belief that the ultimate formulation of string theory would probably be like ordinary field theory. At the time of this statement, the number of vacua according to the conventional wisdom was expected to be small. Currently there has been an increasing number of voices espousing a much larger number of vacua. In some of the current string literature, one can find discussions of ten raised to the power of hundreds as the possible number of vacua [17]. While I cannot quite claim that an infinite number of vacua has become a widely accepted idea, at least we can see motion in this direction.

I believe there is hope for superstring/M-theory to become a normal theory. The Kemmer angles found in my work with Siegel come in two distinct types. One type determines the forces among matter. The other type controls the types of matter given a mathematical description. More recently, mathematical objects called "fluxes" are found to exist in these equations and seem available to describe masses as seen in the laboratory. In my lectures in Poland, I stated one other "irrational" idea:

> *It seems unlikely without a geometrical understanding of string field theory, that much of this mostly unimaginable "new physics" can be studied. A geometrical approach would be helpful to study this question.*

The idea here is that the truly fundamental issues surrounding superstring/M-theory are not likely to be resolved until a genuine paradigm shift of the type that was driven by the introduction of special and general relativity or that of quantum theory. The successful completion of the program of covariant string and superstring field theory seemed and still seems to me the best hope of completing the superstring/M-theory paradigm. This is likely to create a new type of equation (like the Schrödinger equation) capable of generating a truly new paradigm in the field of theoretical physics. To this day, there is a highly specialized little-researched area called string field theory, where, my belief in "irrationality" suggests, will be found the ultimate answers to many of the puzzles in the field. It should be noted that instead of "irrationality," perhaps the word "intuition" might be applicable. On the research boundary, the use of intuition by a scientist is extremely important in performing a benefit/cost analysis of whether to pursue an incomplete idea. To illustrate how this might work, I will conclude this section with one final illustrative tale from the boundary.

During the period of 1982-1984, I had the pleasure of guiding a young graduate student named Barton Zwiebach as he undertook the task of writing a Ph.D. thesis at Caltech. Around 1995, a new topic called "D-p-branes" began to appear in the discussions of superstring/M-theory. By this time, Barton was an untenured professor of physics at M.I.T. and concerned because in all of his work, he had never considered including calculations with "D-p-branes" in his consideration of string field theory. The source of his concern was obvious. Since these mathematical constructs had suddenly appeared, could they be important in efforts to construct the long sought string version of Schrödinger's equation? Although I had not carried out a detailed study of "D-p-branes," my irrational intuition told me they might be (and they have proved to be) useful for studying certain truncations of string theory. However, they did not seem likely to be of fundamental importance to string field theory itself. By 2004, following some brilliant deductions by a physicist named Sen, it was shown that "D-p-branes" did not seem at all important to superstring/M-theory owing to a property they possess called "supersymmetry." [18] In the end, all evidence pointed to "D-p-branes" not being relevant to string field theory nor required to achieve the long sought complete understanding of superstring/M-theory.

With this, I conclude my highly personalized view of a frontier of theoretical science that is still in an incomplete state. Superstring/M-theory, in spite of all the current criticism, is still in my opinion the best bet by far that our species has to make progress in understanding some of the ultimate questions of physics and our creation. One point about which much criticism has been written is that due to various reasons, superstring/M-theory has prevented promising alternatives from being more fully developed. As someone who attempts to keep an open mind about possibly promising approaches and as someone who has no special commitment solely to the idea of superstring/M-theory as the only possibility for providing progress, it has long been my sincere wish to see a competing set of ideas that seems as promising. As I hope my essay has shown, I have long been at variance with large amounts of what has become the conventional wisdom in the area. I have written about this and more importantly offered ideas and suggestions that are alternatives to those of the conventional wisdom. This I believe is the best that any committed theoretical physicist can do. One must offer concrete proposals as simple criticism alone offers no path for exploration.

Superstring/M-theory has an incredibly high "serendipity quotient," quite unlike any putative alternatives. It has shown a remarkable history of producing (yes only mathematical) coincidences that have traditionally been of the type associated with the first rank of mathematical constructions offering us the most profound views of creation. Rather than list many, there is only one with which I wish to close this essay.

The prime motive in the last thirty years of Einstein's research career was his drive to find what he named "the unified field theory." Einstein's theory of general relativity (GR) is, indeed, a theory about space and time, but it is almost a sterile theory in one way. It can be used in such a way as to be like the architectural plans of a magnificent but empty stage. In order for the play we call "physical reality" to unfold, it is necessary to fill that stage with actors. For practitioners of GR, this is done with the use of a device called "the stress-energy tensor." This mathematical construct is used to introduce electrons, photons, quarks, and related "beasts" into Einstein's equation. These are the actors in physical reality and the stuff of which we are made. But in GR, we are only an afterthought. If I may paraphrase Einstein, in the GR theory, God would have had a choice as to whether we should exist or not. These equations can describe a universe composed only of space and time that is mathematically consistent without us. In the confines of such a mathematical construct there arises a question: "Why should any matter, including us, exist at all?"

Superstring/M-theory of the four-dimensional variety in this way is fundamentally different. If the equations that describe our universe are not those given by GR but instead those given by, most especially, a four-dimensional superstring/M-theory, then the universe has no choice! It is a mathematical fact that no superstring capable of describing the three spatial dimensions and one temporal dimension is consistent without also necessarily describing quantities akin to our basic building blocks.

In superstring/M-theory, we are not an afterthought. As GR welded together space and time in an unprecedented way, superstring/M-theory welds together space and time as well as matter and energy in an unprecedented way. Superstring/M-theory says if there is a four-dimensional space-time stage for the performance called physical reality, then that stage must be filled with actors. From general relativity and quantum theory, we see that we are kin and kindred to the stars themselves. Superstring/M-theory says that each of us can trace our familial tree even further to space-time itself, the essence of physical reality. Thus, within the structure of superstring/M-theory, we are more intimately connected to the universe than it is possible to conceive using concepts from any other idea yet proposed.

Granted that at the end of the day, to become a normal theory, superstring/M-theory must confront some observational data about our cosmos. This is the ultimate arbitration in theoretical physics. For the theoretical physicists, unlike the musical composer, it is the audience of nature that counts, not the nature of the audience. Einstein, of course, was well aware of this. But he also was not divorced from philosophical arguments. I believe a philosophical point is also the most profound reason Einstein ardently pursued the quest for the "unified field theory." Using his language, Einstein wanted to know if God had a choice in how the universe was put together. Four-dimensional superstring/M-theory serendipitously answers, "Not as much as could have been," and all other claimed alternatives are silent.

For the reader who wishes to more deeply probe many of the aspects discussed in the final part of this essay, I have recently completed an accessible work aimed at the non-specialist where much detailed discussion can be found. I invite any interested party to pursue this and I hope my efforts in that direction are found to be efficacious [19].

Notes

[1] Portions of this essay derive from "On the Universality of Creativity in the Liberal Arts and Sciences," a paper delivered February 18, 2005 at Westmont College in Santa Barbara, California and published in *Beyond Two Cultures: The Sciences as Liberal Arts. The collected papers delivered at the Fifth Annual Conversation on the Liberal Arts.* Ed. Hoeckley , Christopher (Santa Barbara, CA: Gaede Institute for the Liberal Arts, 2005).

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