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NATURE CONFORMABLE TO HERSELF*

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Why are elegance and simplicity suitable criteria to apply in seeking to describe nature, especially at the fundamental level? Science has made notable progress in elucidating the basic laws that govern the behavior of all matter everywhere in the universe—the laws of the elementary particles and their interactions, which are responsible for all the forces of nature. And it is well known that a theory in elementary particle physics is more likely to be successful in describing and predicting observations if it is simple and elegant. Why should that be so? And what exactly do simplicity and elegance really mean in this connection?

To answer those questions, we need to deal first with the widespread notion that all scientific theory is nothing but a set of constructs with which the human mind attempts to grasp reality, a notion associated with the German philosopher Immanuel Kant. Although I had heard of that belief many times, I first came into collision with it thirty-six years ago in Paris.

At that time, I was a visiting professor at the Collège de France, founded by Francis I more than four hundred years earlier. (As far as I know, I was the first visiting professor in the history of that

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venerable institution.) My office was in the laboratory of experimental physics established by Francis Perrin, a well-known scientist who was a permanent professor at the Collège. On visits to the offices of the junior experimentalists down the hall, I noticed that they spent a certain amount of time drawing little pictures in their notebooks, which I assumed at first must be diagrams of experimental apparatus. Many of the drawings turned out, however, to be sketches of a gallows for hanging the vice-director of the lab, whose rigid ideas drove them crazy.

I soon got to know the sous-directeur, and we conversed on various subjects, one of which was Project Ozma, an early attempt to detect possible signals from other technical civilizations on planets orbiting nearby stars. The corresponding project nowadays is called the Search for Extraterrestrial Intelligence. We discussed how communication might take place if alien intelligences broadcasting signals were close enough to the solar system, assuming that both interlocutors would have the patience to wait years for the signals to be transmitted back and forth. I suggested that we might try beep, beep-beep, beep-beep-beep, etc. to indicate the numbers 1, 2, 3, and so forth, and then perhaps 1, 2, 3,...42, 44.....60, 62.......92, for the atomic numbers of the 90 chemical elements that are stable—1 to 92 except for 43 and 61. "Wait," said the sous-directeur, "that is absurd. Those numbers up to 92 would mean nothing to such aliens.... Why, if they have 90 stable chemical elements as we do, then they must also have the Eiffel Tower and Brigitte Bardot."

That is how I became acquainted with the fact that French schools taught a kind of neo-Kantian philosophy, according to which the laws of nature are nothing but Kantian "categories" used by the human mind to describe reality.

That discussion with the sous-directeur is, in fact, a good starting place for thinking about this matter.

Are the mathematics and the mathematical description of physical phenomena used by an alien technological civilization on another planet likely to resemble what human beings come up with on Earth, even if the notation is very different? At present, we can only speculate about the answer, but the question is deep and meaningful and the speculation can be instructive.

I regard it as likely that there are many advanced civilizations on planets revolving around stars scattered through the universe. Just consider the enormous number of stars in a galaxy and the number of galaxies in the universe; the non-negligible probability of a star possessing a planet something like the Earth; the ease with which complex adaptive systems can then get started as life got started on Earth some four billion years ago; and the fact that the evolution of complex adaptive systems amounts to a search process that allows more and more sophisticated forms to emerge as time goes on. In my view, the main unknowns in the search for extraterritorial intelligence are the actual density in space of the planets on which such intelligence evolves and the length of time that a technical civilization lasts before it destroys itself or ceases to utilize technology. Those unknowns affect the likelihood that an alien technological civilization broadcasting signals is close enough for the signals to be detectable here, but such a civilization may still have evolved somewhere, even if not close by. Thus I believe that the question of what kinds of mathematical science such a civilization can possess is probably a question about the actual universe, even though we may or may not get to compare our answers with any facts.

Are the laws of science just constructs of the human mind so that alien intelligences seeking the laws of nature would most likely arrive at something very different? Or does nature determine to a great extent how an intelligent being would have to describe its laws? And what about the relation of mathematics to science? Need the description of the fundamental laws of nature make use of mathematics as we understand the term, or is there some totally different way of describing the same laws?

These are difficult questions and we cannot give definitive answers to them, but it is instructive to examine the way in which the human scientific enterprise has penetrated deeper and deeper into the domain of the basic laws. As an example of how a new mathematical theory of fundamental physics is discovered, take the case of the Yang-Mills theory, first discussed by Chen Ning (Frank) Yang and Robert Mills about forty years ago. They developed it in the hope that it would contribute somehow to the search for the fundamental laws, but at first it was a purely abstract construct with no known application. It was a generalization of the marvelously successful theory of the electromagnetic field developed by James Clerk Maxwell in the middle of the nineteenth century. A number of us elementary particle theorists showed how to generalize the Yang-Mills idea further to include higher symmetries and also broken symmetries. We also suggested, over the years, ways in which such slightly generalized theories of the Yang-Mills type might actually account for the forces—the so-called strong and weak forces—that were known to exist in addition to electromagnetism and gravitation. Whereas the last two are long-range forces—that is, they die out slowly with increasing distance—the strong and weak forces are short-range, in fact, negligible at distances much larger than the size of an atomic nucleus. Before going further into the uses of Yang-Mills theory, let us review the history of the long-range forces.

Gravitation is universal, in the sense that all matter possesses energy, and all energy is subject to gravitation. Since all matter attracts and is attracted to all other matter, gravitational attractions add up. As a result, gravity is very conspicuous.

Electromagnetism is almost universal. It is produced by—and acts on—electric charges, which are not in short supply: every electron in each atom is electrically charged, and so is every atomic nucleus. However, unlike the gravitational force, the electromagnetic force on a sample of matter does not simply increase with the weight of the sample. Since like electric charges repel and unlike charges attract, a great deal of cancellation takes place in bulk matter, which is nearly electrically neutral. That is why electromagnetic phenomena are somewhat less familiar in the everyday experience of pre-scientific human beings than gravitation, which pulls us all toward the center of the Earth.

It is not surprising that the first force to be described by an adequate theory was the gravitational force, which is both long-range and universal, and that the second one was the electromagnetic force, which is also long-range. Short-range forces were not discovered until the twentieth century, and it is only in the last few decades, with the development of the standard model, that we theoretical physicists have produced a reasonably good picture of those that are known from observation.

Gravitation was fairly well described some three hundred years before Maxwell wrote his equations for electromagnetism. The brilliant theorist who provided the first serious theory of gravitation was, of course, Isaac Newton, who guessed and then demonstrated that the same force with which we are familiar on Earth also governs the motion of the planets and moons. Historians of science still argue over whether it was really an apple falling from a tree on his mother's farm that originally inspired his magnificent insight into the universality of gravitation. But in looking back much later on his discovery of that law, what struck Newton most forcibly was the presence in nature of a kind of consistency. He put it this way:

> How the great bodies of the earth, Sun, moon, and Planets gravitate towards one another what are the laws and quantities of their gravitating forces at all distances from them and how all the motions of those bodies are regulated by those their gravities I shewed in my Mathematical Principles of Philosophy to the satisfaction of my readers: And if Nature be most simple and fully consonant to her self she observes the same method in regulating the motions of smaller bodies which she doth in regulating those of the greater. This principle of nature being very remote from the conceptions of Philosophers I forbore to describe it in that book least I should be accounted an extravagant freak and so prejudice my Readers against all those things which were the main designe of the Book.

Thus, when Newton reflected on the unity of ordinary terrestrial gravity with the force driving the heavenly bodies, he regarded it as an example of the consonance of Nature. We might treat in the same fashion the unity, revealed in Maxwell's equations, of the description of electrical and magnetic phenomena.

But let us not fail to note that the gravitational law of force discovered by Newton has the same form as the law of force for electrical attractions and repulsion found much later by Coulomb. In fact, Newton was thinking along such more general lines when he returned repeatedly in his writings to the idea that Nature is "consonant" or "conformable" to herself. From the Opticks,

> For Nature is very consonant and conformable to her self... For we must learn from the Phaenomena of Nature what Bodies attract one another, and what are the Laws and Properties of the Attraction, before we enquire the Cause by which the Attraction is perform'd. The Attractions of Gravity, Magnetism, and Electricity, reach to very sensible distances, and so have been observed by vulgar Eyes, and there may be others which reach to so small distances as hitherto escape Observation; and perhaps electrical Attraction may reach to such small distances, even without being excited by Friction.

What a wealth of wisdom is contained in these words! Newton suggests that at small distances electrical interactions may play an important role, going far beyond the attraction of bits of paper to an amber rod rubbed against cat's fur. He anticipates the existence of a multitude of short-range forces such as we now know to exist. (Indeed, theoretical considerations now point to an infinite number of such forces.) He points out how empirical laws generally precede detailed dynamical explanations. *And he seems to think of the various "Phaenomena" as exhibiting conformability among themselves as well as within each one.* The last idea is the key to understanding why the criterion of simplicity should be helpful in the search for the fundamental laws of physics.

In discussing why that is so, let us make use of the familiar metaphor that relates the successive discoveries in fundamental physics at higher and higher energies (or, what is the same thing, at shorter and shorter distances) to the peeling of an onion. Removing the skins of the onion one by one, we encounter similarities between one layer and the next. We have remarked that over the centuries, in passing from the gravitational force to the electrical one (under familiar "nonrelativistic and classical" conditions), scientists observed a noticeable similarity between these forces: both fall off with the square of the distance. During the last few decades, in going from electromagnetic theory to the combined theory of the weak and electromagnetic forces and to the theory of the strong force, we have encountered profound similarities in proceeding from Maxwell's equations to slight generalizations of the equations of Yang and Mills, which are themselves an ingenious generalization of Maxwell's equations. The type of theory has not been drastically altered.

As we peel the skins of the onion, penetrating to deeper and deeper levels of the structure of the elementary particle system, mathematics with which we become familiar because of its utility at one level suggests new mathematics, some of which may be applicable at the next level down—or to another phenomenon at the same level. Sometimes even the old mathematics is sufficient.

A generalization may be performed by a theoretical physicist, or by a mathematician, or by both working in ignorance of each other's efforts. But the usefulness to science of a generalization is not just a function of these human activities. It depends on the fact that nature actually exhibits similarities between one level and the next, between one skin of the onion and the next. That is what Newton, with remarkable precocity, apparently noticed. The fundamental laws of nature are such that a rough self-similarity prevails in the set of effective theories that approximately describe the successive layers.

Now we can return to the question of why simplicity is a useful criterion to apply in the search for the fundamental laws of physics. Simplicity, of course, is the opposite of complexity. In discussing the simplicity of a theory, we are referring to the near-absence of what I have called effective complexity. The effective complexity of a thing means the length of a very concise description of its regularities. Of course, any such definition is somewhat context-dependent. For instance, the length of the short description depends on the language employed and on the knowledge and understanding of the world that is assumed. But that is just the point. Since the mathematics needed to describe one skin of the onion is similar to that already developed for the previous skins, the new theory can be very concisely written in notation already familiar from earlier work. One reason the Yang-Mills equations look simple and elegant is that they are easily described in mathematical language suitable for Maxwell's equations.

But where does this process of peeling the onion end? It seems likely today that it ends in the discovery of a unified theory of all the forces of nature. In fact, it is possible that we have already achieved that goal in the form of superstring theory. For the first time in history, we have a plausible candidate for the role of unified quantum field theory of all the elementary particles and interactions. That theory correctly predicts Einstein's sophisticated general-relativistic theory of gravitation (which replaced Newton's some eighty years ago), and it does so within the framework of quantum mechanics without producing the preposterous infinite corrections to calculations that plagued previous attempts to quantize Einsteinian gravitation.

Superstring theory predicts an infinite number of kinds of forces; all but a finite number, however, are too short-range to be detected by experiment in the foreseeable future. Many of the predicted short-range forces that are detectable, including the strong and weak forces already known, are describable in superstring theory by means of mathematics similar to that of the Maxwell or Yang-Mills equations. Moreover, Einstein's theory of gravitation shares with both Maxwell and Yang-Mills theory and with superstring theory itself the very important mathematical property of being a gauge theory.

We can now turn the story around. We can start from the heart of the onion—the simple unified quantum field theory of all the elementary particles and their interactions, whether it is superstring theory or something else—and work outward. That fundamental unified theory is not only simple. It also has the property that its consequences exhibit similarities between skins of the onion, that is, between phenomena (forces, for example) that are conspicuous in one range of energies or distances and in another. Those similarities, which relate the mathematics useful in one context to the mathematics useful in another, can be regarded more as intrinsic properties of the underlying fundamental law than as flowing from the properties of the human mind (or of any other intelligence investigating the basic laws of nature).

In summary, then, we have this picture of the laws of physics: A simple unified theory (which may well be superstring theory) describes all the elementary particles and all the forces of nature. It is a property of nature, not of the human mind, although the way it is formulated by human beings may be peculiar to our species. It has the characteristic that its various manifestations in different ranges of energy or distance possess a great deal of similarity to one another and to the underlying theory itself. The mathematical structure of the unified theory is reflected in certain properties of the structures needed to describe those manifestations. Any group of intelligent beings attempting to describe the system is likely to be working in from large distances or up from low energies and will encounter these manifestations successively. Because of the similarity of these manifestations, those beings will find it natural to keep generalizing their mathematics, and the successive steps will appear fairly simple. If the beings persist, they are likely to discover the fundamental unified theory with its essential mathematical structure, which will explain the other structures encountered along the way and their similarities. That basic law is, then, what is responsible for the usefulness of certain kinds of mathematics in physics. Intelligent beings on another planet can arrive at the same law, even if each of them has seven tentacles, thirteen sense organs, and a brain shaped like a pretzel. Of course, their notation is very unlikely to resemble ours, but we already know from many examples that what is essentially the same mathematics can often be expressed in very different ways.

All three principles—the conformability of nature to herself, the applicability of the criterion of simplicity, and the utility of certain parts of mathematics in describing physical reality—are thus consequences of the underlying law of the elementary particles and their interactions. Those three principles need not be assumed as separate metaphysical postulates. Instead, they are emergent properties of the fundamental laws of physics.

In my opinion, a great deal of confusion can be avoided, in many different contexts, by making use of the notion of emergence. Some people may ask, "Doesn't life on Earth somehow involve more than physics and chemistry plus the results of chance events in the history of the planet and the course of biological evolution? Doesn't mind, including consciousness or self-awareness, somehow involve more than neurobiology and the accidents of primate evolution? Doesn't there have to be something more?" But they are not taking sufficiently into account the possibility of emergence. Life can perfectly well emerge from the laws of physics plus accidents, and mind, from neurobiology. It is not necessary to assume additional mechanisms or hidden causes. Once emergence is considered, a huge burden is lifted from the inquiring mind. We don't need something more in order to get something more.

Although the "reduction" of one level of organization to a previous one—plus specific circumstances arising from historical accidents—is possible in principle, it is not by itself an adequate strategy for understanding the world. At each level new laws emerge that should be studied for themselves; new phenomena appear that should be appreciated and valued at their own level.

It in no way diminishes the importance of the chemical bond to know that it arises from quantum mechanics, electromagnetism, and the prevalence of temperatures and pressures that allow atoms and molecules to exist. Similarly, it does not diminish the significance of life on Earth to know that it emerged from physics and chemistry and the special historical circumstances permitting the chemical reactions to proceed that produced the ancestral life form and thus initiated biological evolution. Finally, it does not detract from the achievements of the human race, including the triumphs of the human intellect and the glorious works of art that have been produced for tens of thousand of years, to know that our intelligence and self-awareness, greater than those of the other animals, have emerged from the laws of biology plus the specific accidents of hominid evolution.

When we human beings experience awe in the face of the splendors of nature, when we show love for one another, and when we care for our more distant relatives—the other organisms with which we share the biosphere—we are exhibiting aspects of the human condition that are no less wonderful for being emergent phenomena.