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PHYSICS AND BEAUTY

What follows is a translation of an article by Chinese astrophysicist Fang Lizhi which appeared in *Wénxué Pinglùn* ("Literary Review"), May 1988. Fang has published widely in physics journals all over the world; his research includes areas such as solid state physics, laser physics, and cosmology. This is one of his few non-technical articles.

Known as the "Chinese Sakharov," Fang Lizhi took advantage of his international fame as a physicist to openly criticize the Chinese government in numerous speeches and articles throughout the last two decades. In the years before the Tiananmen Square crackdown he came under increasing attack from the authorities. In January of 1987 he was purged from the Communist Party and lost his post as vice president of the Hefei Institute of Science and Technology. He was in the international news again in February of 1989 when the Chinese police prevented him from attending an official banquet hosted by George Bush during the president's visit to China. After the Tiananmen Square massacre, Fang Lizhi and his wife, physicist Lu Shuxian, avoided almost certain arrest by taking refuge in the American embassy in Beijing, where they remained in protective custody for several months. Their presence in the embassy was a source of increased tension between Beijing and Washington, and after a series of complex negotiations, Fang and his wife were allowed to fly to England, where Fang took a post at Cambridge University. He has continued to be an outspoken proponent of political reform in China, and has made headlines by criticizing the American government for its lenient treatment of the Chinese leadership.

The following article, like most scholarly articles in China, gives no references for the quoted passages. I have tried whenever possible to find the quotation in the original language, but where that was

not possible I was forced to translate or backtranslate the quotation in question from Fang's Chinese. Since he cannot return to China to retrieve his books and source materials, Fang suggests to me in a letter that this lack of certain references might have to serve as "a little souvenir of the current situation."

I would like to thank Greg Huber of the Physics Department at Boston University for his help in tracking down many of the original sources for the quotations. Also thanks to Yan Yong at Stanford University for checking the translation.

David Moser

Beauty is not the exclusive property of domains such as literature, art, and religion; it also belongs to physics. In fact, the first established group of esthetes among the ancient Greek philosophers was the Pythagorean School, which was composed of mathematicians, astronomers, and physicists.

"Beauty" is still a common word in the vocabulary of physics. When a paper is read at a conference or a published scientific result is evaluated, one often hears phrases such as "a *beautiful* theory," or "a model which is much more *elegant* than the previous one." The sense of "beauty" or "elegance" referred to in such cases is very much akin to the kind of esthetic reaction one has when hearing a piece of music or viewing a work of art. Although this esthetic sense within the realm of science is hard to pin down or formalize, it is nevertheless something felt by almost everyone who has undertaken the study of physics.

Ludwig Boltzmann had the following reaction to the work of James Clerk Maxwell:

A musician, upon hearing the first few measures of a piece of music, can distinguish whether the piece is by Mozart, Beethoven, or Schubert. In the same way, a mathematician, upon reading the first few pages of a proof, can tell whether it is the work of Cauchy, Gauss, Jacobi, or Helmholtz. A high degree of external elegance, with sometimes the feeblest underlying skeletons of conclusions, characterizes the French, whereas the English, especially Maxwell, are characterized by a great dramatic force. Who does not know Maxwell's dynamical theory of gases? First, the variations of the velocities majestically develop. Then from one side the equations of state make their entrance, from the other side enter the equations for central motion,

and the chaos of formulas surges higher and higher. Suddenly the four words resound: "Put $n=5$." The malevolent demon V [*velocity*] vanishes, just as if in a piece of music a wild, continually disruptive figure in the basses had become silent. As if by a stroke of magic, all that previously seemed uncontrollable is put in order. There is no time to say why this or that substitution is made: let anyone who does not *feel* it lay the book down. Maxwell is no producer of program music; he does not need to provide explanatory notes. The formulas freely spew forth result after result, until, in a final surprising effect, the thermal equilibrium of a heavy gas is obtained, and the curtain falls.¹

Bertrand Russell described mathematics in the following terms:

Mathematics, rightly viewed, possesses not only truth but a supreme beauty—a beauty cold and austere, like that of sculpture, without appeal to any part of our weaker nature, without the gorgeous trappings of painting or music, yet sublimely pure, and capable of a stern perfection such as only the greatest art can show. The true spirit of delight, the exaltation, the sense of being more than man, which is the touchstone of the highest excellence, is to be found in mathematics as surely as in poetry.²

To be sure, a quest for beauty, for pleasure, for an enhancement of the intellect, is for many scientists the direct impetus for their research.

There are two sharply contrasting aspects to the study of those natural sciences which include astronomy and physics. On the one hand, science is the basis for all technological advancement, and thus has enormous practical value to society, in that technological progress greatly facilitates the production of goods and products. On the other hand, the *motivation* for scientific research is completely divorced from the goal of technological advancement itself. The latter is invariably concerned with practical applications, whereas the former more resembles an artistic endeavor—it arises from the search for and creation of beauty.

Copernicus, the founder of modern astronomy, states clearly at the outset of his landmark work *De revolutionibus orbium coelestium* (On the Revolution of the Heavenly Spheres):

Among the many various literary and artistic pursuits which invigorate men's minds, the strongest affection and utmost zeal should, I think, promote the studies concerned with the most beautiful objects, most deserving to be known.³

The French mathematician and physicist Henri Poincaré is much revered in the scientific world, despite the fact that Lenin once pronounced him "a great scientist but a negligible philosopher." There is a famous quotation by Poincaré concerning motivation in scientific research which has become one of the classic statements on the subject:

The scientist does not study nature because it is useful: he studies it because he delights in it, and he delights in it because it is beautiful. If nature were not beautiful, it would not be worth knowing, and if nature were not worth knowing, life would not be worth living . . . [I]ntellectual beauty is sufficient unto itself, and it is for its sake, more perhaps than for the future good of humanity, that the scientist devotes himself to long and difficult labors.⁴

Of course, the value of science lies in its accordance with truth; that is, in its ability to explain already known phenomena and to predict future events. Science must always be able to stand up to observations and empirical tests. This empirical standard is obviously not to be equated with a search for beauty per se, so what does it mean to say that the search for beauty is, at least in part, synonymous with the search for truth?

I'd like to make use of some famous examples in the history of science to address this question. All of the following accounts seem to make one point clear: The universe, or Nature, has the property that all truths are necessarily beautiful. Perhaps this statement cannot be considered a well-defined scientific truth, but it can at least be stated as an effective and workable research heuristic thus: "The pursuit of beauty will inevitably lead to the discovery of truth." Throughout history, this heuristic has achieved a series of successes, and sometimes rather spectacular ones.

The first example I will deal with is the theory of a round earth. Statements about a spherical earth can first be seen in the writings of the ancient Greeks, and Western astronomy later came to embrace this view, which is encountered often in various classical texts. By contrast, in ancient China the concept of a round earth was never clearly formulated, though some of the commentary found in certain ancient writings can perhaps be interpreted as implying such a theory. Yet nowhere in Chinese tradition can one find an image of a round earth. Three-dimensional models such as those found in the Temple of Heaven in Beijing, which depict the heavens as a sphere

and the earth as a flat square, are representative of the unvarying Chinese orthodox view.

The reason for this difference in Chinese and Western astronomy can perhaps be attributed to different cultural concepts of beauty. Two thousand years ago, neither the Chinese nor the Greeks had anything that could be considered direct empirical evidence on which to base a round-earth conjecture. (Only later, when Columbus discovered America, and Magellan circled the globe, was there indisputable proof of the notion.) The Chinese and Greeks in ancient times had only a small number of astronomical observations on which to base their hypotheses about the shape of the earth.

What is interesting is that two astronomers, when confronted with the same observed phenomenon, can arrive at two very different conclusions. The Greeks and Chinese both observed that the sun is lower in the sky at noon in the north than it is in the south. The model of a round earth seemed satisfying and plausible to the Greeks because they had completely absorbed Pythagorean notions concerning the harmony of the universe, and because it seemed evident to them that circles and spheres were the most perfect shapes in nature. The Greeks went even further and used the difference in the sun's height in the north and south to estimate the earth's radius, arriving at results that are very close to modern measurements.

The Chinese astronomers realized that this discrepancy in the sun's angle in the north and south indicated that the earth was not perfectly flat, but rather than hypothesize that the earth might be spherical, they adopted a compromise model. Perhaps, they reasoned, the cities in which we dwell indeed rest on a surface that is somewhat curved, *but the earth as a whole is still flat*. According to the Chinese model, the land could be conceived of as a slice of a hemisphere floating in a flat ocean. Therefore, even though Chinese measurements of the difference between the angle of the sun in the northern and southern sky were no less accurate than those of the Greeks, the Chinese never used these measurements to calculate the radius of the earth, since, of course, they never actually envisioned the earth as being spherical.

It is thus clear that creativity in scientific thinking depends much upon the image one has of the world, and one's image of the world is influenced by one's cultural background. It is precisely in this way that cultural concepts of beauty can exert a shaping influence on scientific progress. Ernst Mach once wrote:

In studying nature, we cannot help but apply our knowledge of the interrelationships between the various phenomena under investigation. What we imagine to be the underlying causes for the observed phenomena is limited by our understanding of the world . . . The fact that observed phenomena often appear random or arbitrary to us makes our perception particularly susceptible to the vagaries of our cultural background.⁵

The theory of the round earth is the first famous triumph of the culturally-influenced world view that sees the universe as fundamentally beautiful and harmonious.

A second famous example is the heliocentric model of the universe. A longstanding popular view of epistemology is that the course of human knowledge rather consistently follows the sequence "experience → understanding → further experience → greater understanding." Throughout the literature subscribing to this epistemological model, the development of the theory of the heliocentric solar system has always been attributed to the fact that the earlier earth-centered model ran into difficulty in explaining and predicting the observed movements of celestial bodies, and thus the heliocentric view was developed. This account, however, is simply not historically accurate.

What compelled Copernicus to develop the heliocentric model actually had nothing to do with any supposed superiority of the sun-centered model in explaining the movements of the celestial bodies. In fact, all of the observations explained and predicted by the heliocentric model could be dealt with by the earth-centered model as well, and wherever there were snags with the earth-centered model, there were similar problems with the sun-centered model. In addition, the predictions yielded by Copernicus's heliocentric theory were *not* as accurate as those of Ptolemy's earth-centered theory. Thus, nowhere in the process that led Copernicus to his theory is there much evidence for the "further experience → greater understanding" epistemological model just mentioned.

To be sure, if one applies celestial mechanics to the problem, then the heliocentric model emerges as vastly superior to the earth-centered model. But celestial mechanics was developed only in the hundred years after Copernicus's death, and played no role in the formulation of his theory.

What compelled Copernicus to envision a heliocentric system? Quite simply, its beauty. What was most attractive about Coperni-

cus's new model, and what made it superior to the earth-centered model, was its simplicity and consistency. Within the earth-centered theory of Ptolemy, the movements of the celestial bodies could only be explained with recourse to a complicated system of cycles and epicycles. In the heliocentric theory, the notion of epicycles was completely discarded, and the orbit of each of the moons and planets was seen as a perfect circle.

Copernicus states straightforwardly in his *De revolutionibus orbium coelestium* that what drove him to formulate his theory was not so much a need to achieve greater accuracy in his calculations, but rather a desire to develop a model of the universe that would be "perfect in form" and possessing a "marvelous symmetry."

The third example I will deal with involves Johannes Kepler, who considered himself a Pythagorean. He once wrote:

The movement of the heavenly bodies is like a great song, a continuous, many-voiced song. It is a song that must be appreciated through intellect and reason, rather than experienced directly through the sense of hearing. This music, through its modulation and cadence, and according to the working-out of a fixed, pre-ordained six-voice counterpoint, seems to measure and delineate the passage of time.⁶

It must be stressed that Kepler's description of the motion of the planets as a kind of song is not merely a fanciful literary metaphor, but was an intrinsic part of his research methodology. In many of his works on astronomy Kepler actually employs musical staff notation, often using the language of music rather than words to explain his ideas. The velocities and orbital movements of the individual planets are often described in terms of musical intervals and meters, and many of the names given to his various laws of motion come from the musical diagrams he employed.

It is clear that in the context of Kepler's research, beauty is not merely a thread which runs in parallel lines through both the domains of music and astronomy, but rather a bridge connecting the two disciplines.

Twentieth-century physics also makes use of this "esthetic bridge." In the latter part of the 1920s, shortly after the birth of quantum mechanics, a young English physicist, P. A. M. Dirac, formulated an equation that described the movement of the electron. One of the most important conclusions of this elegant equation was that there must be a perfect symmetry between positive and negative charges

in nature. This meant that since there was an electron which carried a negative charge, then there must perforce exist a corresponding positively-charged particle, and furthermore, the masses of the two particles must be identical. However, although there was already ample evidence at the time of Dirac's result that the amount of positive and negative charge in nature was the same, the various positively-and negatively-charged particles did not seem to meet the symmetry requirements of the Dirac equation; there was an enormous difference between the mass of the negatively-charged electron and that of the positively-charged proton. For this reason, some physicists at first did not accept the Dirac equation, but Dirac himself and many others felt that it was simply too beautiful to discard. Several years later, a new particle—the positron—was discovered, and the characteristics of this particle accorded perfectly with the predictions of the Dirac equation—another vindication of the faith in the beauty of nature's laws. The events surrounding the prediction and subsequent discovery of the positron constitute the historical backdrop for the following remarks by Dirac:

I think there is a moral to this story, namely that it is more important to have beauty in one's equations than to have them fit experiment It seems that if one is working from the point of view of getting beauty in one's equations, and if one really has a sound insight, one is on a sure line of progress. If there is not complete agreement between the results of one's work and experiment, one should not allow oneself to be too discouraged, because the discrepancy may well be due to minor features that are not properly taken into account, and that will get cleared up with further developments of the theory.⁷

Which is to say that accordance with experimental observation is not the only standard for the value of a scientific result. Sometimes, as Dirac says, "it is more important to have beauty in one's equations than to have them fit experiment." It is for this reason that the physics journals do not balk at printing results that are at odds with prevailing experimental evidence.

In 1954, C. N. Yang and his partner Robert Mills wrote a paper on gauge symmetry that contained results that were completely at odds with experimental evidence. According to the Yang-Mills theory, there had to exist a particle with a rest mass of zero, but all experimental evidence had excluded such a possibility. Despite this, the theory was welcomed by the physics community and published.

The symmetry of the Yang-Mills theory—known as "gauge field theory"—was simply too attractive to be ignored. Gauge field theory became a rather lively field in the 1960s, and throughout the last twenty years, during the development of the search for the fundamental laws of mechanics, no facet of physics has been untouched by the theory of gauge symmetries. The modern age of the study of high-energy physics has even been classified as the era of the gauge field theory.

Here again, the "beauty" criterion has sidestepped the narrow standard of "experimentalism"—the notion that the experiment is all-important. Yang has come up with another beautiful result that falls out of the gauge field theory, namely the existence of "magnetic monopoles." The existence of magnetic monopoles is still in doubt, however, because no researcher has yet been able to observe them in nature. Yang's response to these doubts has been to maintain that the prediction is so satisfyingly beautiful that it is impossible to imagine that nature would *not* have magnetic monopoles.

One of the tasks of modern physics is to come up with a TOE, a "Theory of Everything"; that is, a unified theory of the laws of mechanics. The physics world is quite confident that such a unified theory can eventually be developed, since the history of physics is simply an unbroken series of successes in finding greater and greater unified theories.

One of the difficulties in formulating a TOE is that one cannot, of course, directly carry out experiments concerning such a theory in the laboratory. So what principles can be used to structure a TOE? What standard can be used to judge the value of such research? Once again, one has to draw upon aesthetic considerations.

At present, the most optimistic of those in search of a TOE is the group involved with "superstring theory," a domain which has attracted the most talented particle physicists and astrophysicists of the new generation. The fundamental faith of these physicists is that a theory in accord with the following conditions might possibly be unique, and thus based upon these conditions one could ascertain the origins of the universe. These conditions are:

1. *Harmony*; the theory must be one in which the universe exhibits the highest and most ideal symmetry.
2. *Completeness*; it must give a complete account of all the mutually interacting forces in the universe.

3. *Consistency*; it must be a theory in which the universe exhibits a high degree of internal unity and regularity, with all the parts acting in accord with one another.

It can almost be said that superstring theory adheres to, in the most classic sense, the esthetic principle of Pythagoras:

Harmony + Completeness + Consistency = Truth

I do not wish to give the impression that beauty in physics is to be equated only with symmetry. Quite the contrary, physics often investigates phenomena that are highly chaotic and random, as well as ones which exhibit a high degree of symmetry. Einstein's 1905 paper on special relativity revealed profound symmetries involving time and space, the relative and the absolute. Yet in the same year he published a paper on Brownian motion, presenting an extremely refined theory about one of the most random of processes in nature.

If it can be said that the ancient physicists preferred explanations that drew upon the principles of regularity, proportion, and balance, then modern physicists seem equally drawn to disorder, chaos, and disequilibrium. In the nineteenth century we have mathematician Charles Hermite, who once said, "Things that are not elegant have no place in rigorous science; they are merely rubbish."⁸ By contrast, the modern physicist John A. Wheeler said, "It is possible to believe that no one will be considered scientifically literate tomorrow who is not . . . familiar with fractals,"⁹ fractals here being equated with extreme inelegance.

Is there any beauty to be found in disorder, chaos, and disequilibrium? In the words of Hermann Weyl, "Asymmetry is almost never due to a complete absence of symmetry."¹⁰ Interestingly, in the arts it is often noted that perfect symmetry is usually not the most desirable or beautiful state of affairs. Rather, what is most satisfactory is some *combination* of symmetry and disorder. And perhaps it can even be said that modern physics has already begun to discover evidence for this esthetic "formula."

As one might expect, modern physics is now devoting itself to understanding the relationship between symmetry and asymmetry, regularity and disorder, equilibrium and disequilibrium, order and chaos. What has been discovered so far is that symmetry can spontaneously give rise to asymmetry, that there is an essential order underlying chaos, that equilibrium depends upon disequilibrium,

and that organization can arise out of randomness. In modern art and music, harmony often comes from dissonance, disjointed rhythms arise out of strict meter, and chaotic fragments come together to create a sense of unity. All this seems to indicate that these works are in some sense created in accordance with the esthetic principles in physics outlined above.

David Bohm has this to say about the relationship of physics to art: "Physics is a form of intuition, just like a form of art."¹¹ And the form this intuition takes involves creativity, structuring, and a free play of the imagination. Careful experiments and an accumulated body of observations are essential to physics, yet sheer imagination also plays an important role. The English physicist John Tyndall said, "Accurate experiments and observations constitute the foundations of the edifice of science, but imagination itself plays the role of the architect."¹² Einstein voiced this position in even clearer terms:

If then, it is true that this axiomatic basis of theoretical physics cannot be extracted from experience but must be freely invented, can we ever hope to find the right way? . . . I am convinced that we can discover by means of purely mathematical constructions the concepts and the laws connecting them with each other, which furnish the key to the understanding of natural phenomena. Experience may suggest the appropriate mathematical concepts, but they most certainly cannot be deduced from it. Experience remains, of course, the sole criterion of the physical utility of a mathematical construction. But the creative principle resides in mathematics. In a certain sense, therefore, I hold it true that pure thought can grasp reality, as the ancients dreamed.¹³

All in all, physics embodies two opposite ends of a spectrum, and the development of physics has drawn upon the contributions of both these extremes. These polar opposites are exemplified by such complementary pairs as: experimentation vs. imagination, logic vs. intuition, as well as objective facts vs. subjective esthetic judgment. My earlier examples from classical and modern physics also serve to point out the interdependence and contingent nature of these sets of opposites. There are many other examples in the history of physics.

It can even be said that the close interrelatedness and interdependence of objective facts and subjective esthetic judgment is *itself* one of the great beauties of physics. The basis for this beauty lies in the fact that these opposites are merely two sides of the same coin. Einstein very early on realized this, when he said, "The most incom-

prehensible thing about the universe is the fact that it is comprehensible." From this statement we can perhaps derive two logical deductions:

We are only capable of understanding a universe in which beings capable of understanding it could evolve.

The only kind of universe that is understandable is one that is able to evolve beings capable of understanding it.

Perhaps these two mutually-dependent inferences constitute evidence for the compatibility of objective fact and esthetic judgment.

Beijing Observatory
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Translated by David Moser

NOTES

¹Ludwig Boltzmann, *Populäre Schriften* (Leipzig: Johann Ambrosius Barth, 1905), p. 73. (My translation).

²Bertrand Russell, quoted in Morris Kline, *Mathematics in Western Culture* (New York: Oxford University Press, 1953), p. 5.

³Nicholas Copernicus, *On the Revolutions of the Heavenly Spheres*, Jerzy Dobrzycki, ed., translated by Edward Rosen (Baltimore: John Hopkins Press, 1978).

⁴Henri Poincaré, *Science and Method*, in *The Foundations of Science*, George Bruce Halsted, trans. (Lancaster: The Science Press, 1946), pp. 366-7.

⁵Ernst Mach, *Knowledge and Error: Sketches on the Psychology of Enquiry*, Brian McGuinness, ed., translated by Thomas J. McCormack and Paul Foulkes (Boston: D. Reidel, 1975), p. 38.

⁶Johannes Kepler, *Harmonices Mundi*. My translation from Fang Lizhi's Chinese.

⁷P. A. M. Dirac, "The Physicist's Picture of Nature," *Scientific American*, May 1963, p. 45.

⁸My translation from Fang Lizhi's Chinese. Source not found.

⁹John A. Wheeler, book review of Mandelbrot's *The Fractal Geometry of Nature*, in *American Journal of Physics*, Vol. 51, No. 3, March 1983, p. 286.

¹⁰My translation from Fang Lizhi's Chinese. Source not found.

¹¹My translation from Fang Lizhi's Chinese. Source not found.

¹²My translation from Fang Lizhi's Chinese. Source not found.

¹³Albert Einstein, "On the Method of Theoretical Physics," *Essays in Science* (New York: Philosophical Library, 1933), pp. 17-18.