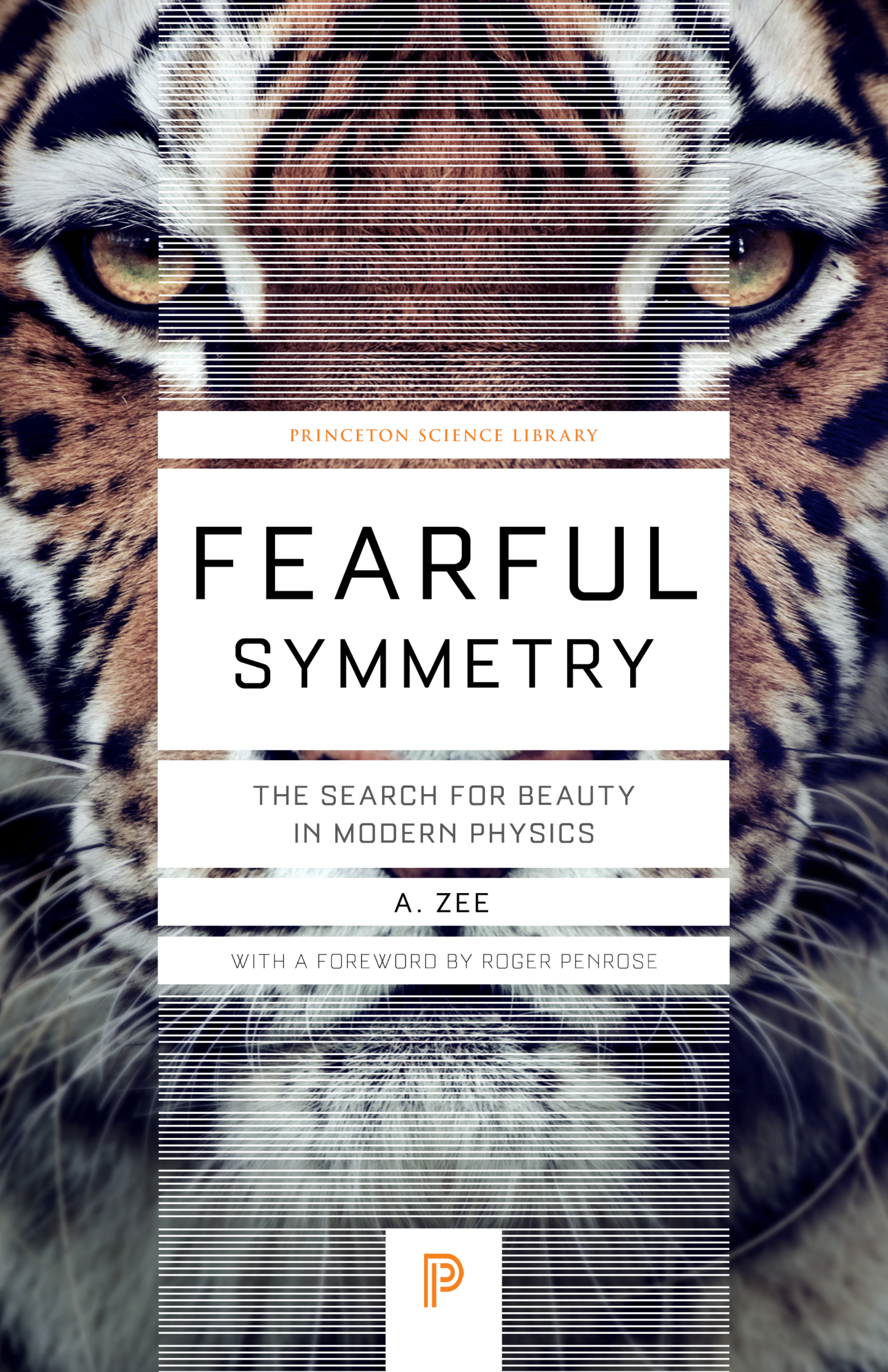

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FEARFUL SYMMETRY

THE SEARCH FOR BEAUTY IN MODERN PHYSICS

A. ZEE

WITH A FOREWORD BY ROGER PENROSE

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SYMMETRY

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The Search for Beauty in Modern Physics

With a new foreword by Roger Penrose

A. Zee

PRINCETON UNIVERSITY PRESS
Princeton and Oxford

Published by Princeton University Press, 41 William Street, Princeton, New Jersey 08540
In the United Kingdom: Princeton University Press,
6 Oxford Street, Woodstock, Oxfordshire OX20 1TR

First published by Macmillan Publishing Company, 1986
First Princeton edition, for the Princeton Science Library, 1999
Reprinted, with a new foreword, 2007
New Princeton Science Library edition, 2016
Paperback ISBN: 978-0-691-17326-9

The Library of Congress has cataloged the first Princeton edition as follows
Zee, A.
Fearful symmetry : the search for beauty in modern physics / A. Zee.
p. cm.
With a new preface and afterword.
Originally published: New York : Macmillan Pub. Co., 1986
Includes bibliographical references and index.
ISBN 0-691-00946-5 (pb. : alk. paper)
1. Symmetry (Physics) 2. Physics—Philosophy. 3. Renormalization (Physics)
I. Title.
QC174.17.S9Z4 1999
530.1—dc21 99-44882

Printed on acid-free paper. ∞

press.princeton.edu

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

To Gretchen

Tyger! Tyger! burning bright
In the forests of the night,
What immortal hand or eye
Could frame thy fearful symmetry?

—William Blake
(From *Poems of William Blake,*
edited by W. B. Yeats. London:
G. Routledge & Sons, 1905.)

Contents

Foreword

The notion of *symmetry* has manifestations that are widespread in human culture. Symmetry also exhibits itself in a great many features of the operation of the Natural world. It is a notion that is simple enough to be understood and made use of by a young child; yet it is subtle enough to be central to our deepest and most successful physical theories describing the inner workings of Nature. Symmetry is thus a concept that is simultaneously obvious and profound.

Symmetry has many areas of application. Some are basically practical, such as those made use of in engineering—for example, with the bilateral symmetry of most aeroplane designs or in the symmetry in bridge construction—or, at a more mundane level, in the satisfactory creation of furniture. But other uses of symmetry are more evidently purely aesthetic, and can be central to many artistic creations, where it may provide a key ingredient underlying the sublime beauty of various great works of art. Moreover, this is true over a considerable range of disciplines, such as in painting or sculpture, or in music or literature. In mathematics, the notion of symmetry is the starting point of vast areas of deep theory, providing much penetrating insight of enormous scope. In the science of crystallography it is crucial, as it is also in many aspects of chemistry. It is evident to the eye that symmetry is also important to biological function. There is great symmetry to be found throughout the plant and animal kingdoms, and this symmetry can contribute in many different ways to the efficient functioning of an organism. Bilateral symmetry, for example, is almost universal among animals. Yet it is occasionally grossly violated, such as in the twisting spiral shape of a snail's shell. But with such a shell, we find that there emerges a deeper type of symmetry, not evident at first: a symmetry under rotational motion, provided that this is accompanied by uniform expansion or contraction.

It is in modern fundamental physics, though, that we find the most subtle interplay between symmetry and asymmetry, for, as twentieth-century physics has revealed, there is a special role for symmetry in Nature's basic forces that is both central and sometimes enigmatically violated. Some of the underlying ideas are quite simple to grasp, but others, distinctly sophisticated. However, I believe that this undoubted sophistication should not be held as a reason for denying the lay public an opportunity to access some of these ideas, which often exhibit a kind of sublime beauty. Yet, it is not so easy to present such ideas in a way accessible to a lay reader, while at the same time holding the reader's interest and conveying some nontrivial understanding. Tony Zee, however, achieves this in a masterful way in his classic, here reprinted, *Fearful Symmetry: The Search for Beauty in Modern Physics.*

Fundamental physics is genuinely difficult, and the crucial role of symmetry is often a subtle one. For this good reason it is not often satisfactorily explained to a lay audience at length or in significant depth. In the arts, on the other hand, it is usually not hard to produce accessible works fully extolling the use of various qualities of symmetry, often merely by use of a good picture, as is the case also in architecture and engineering. This seems to be true as well in biological descriptions and in books depicting the natural beauty of crystalline substances. There are even many popular works in which the symmetrical forms of pure geometry, or of other areas of pure mathematics, can be made very accessible even to the mathematically unsophisticated reader. But there is something especially hard to communicate about the roles of symmetry in basic physics, particularly because these roles are often very abstract and they frequently depend upon the highly nonintuitive and confusing fundamental principles of *quantum mechanics*. The demands of quantum physics are themselves not easy to comprehend. They are often subtle, and have a special importance to the workings of Nature at the deepest levels that human understanding has yet been able to penetrate. It is when the ideas of symmetry and quantum mechanics come together that we find the special subtleties that are crucial to our modern understanding of the basic forces of Nature.

All this serves to emphasize the difficulties that confronted Zee's task, and to enhance our admiration for his superb achievement. But there is one thing to his advantage that he was able to exploit: the fact that symmetry and *beauty* are closely linked. By emphasizing the beauty in the use of symmetry that lies behind our modern theories of the forces of Nature, rather than dwelling on the mathematical details, he is able to side-step most of the technicality and many of the deep remaining difficulties that presently confound further progress. This is a story that, indeed, has not reached its end, as it is still beset with enigmas and apparent inconsistencies. Of course, this makes it all the more fascinating to study the progress that has been made so far, and perhaps to entice more readers to enter, in a serious way, this wonderful world—a world that that they may not have considered before.

And for this, Tony Zee here serves as a superb guide!

Roger Penrose
March 2007

Preface 1999

I am happy that I decided to write *Fearful Symmetry.* During a visit to the University of Texas in 1984, I was chatting with the eminent physicist Steve Weinberg when his secretary brought him his mail, which happened to contain a review of his second popular physics book. Our conversation naturally turned to writing popular physics books. Various physicists had encouraged me to write a textbook, on quantum field theory in particular. Not only did Weinberg encourage me to write a popular physics book instead, he also introduced me to his publisher and offered valuable advice. Thus, a few months later I found myself having lunch in New York with Weinberg's publisher. I was told to bring a sample chapter, which I chose to devote to conservation laws; it started with the sentence "There is no free lunch." The publisher laughed and said, "There is." Since then I have been taken to lunch and dinner by various publishers, editors, and agents, and I have also re-learned that in some sense there is indeed no free lunch. The curious reader will find the sentence about free lunch in Chapter 8, although it no longer starts the chapter.

I am happy that I wrote *Fearful Symmetry* because of all the wonderful letters (and even presents) I have received from appreciative readers, because of all the ego-warming reviews, because of the pleasure of hearing my words read by a professional actor in a Library of Congress audio tape for the blind, and because of seeing my immortal prose translated into several foreign languages but, most of all, I am happy because the book allowed me to get out of the physics community once in a while. I was invited to lecture about symmetry at all sorts of interesting places, for example at the National Center for the Performing Arts in Bombay, where I learned about symmetry in classical Indian dances, and at the Berlin Academy of Arts, where I was invited to participate in an international symposium on racism. (What racism has to do with symmetry is not clear to me.) *Fearful Symmetry* launched my career as a writer. The pages I cut out of my manuscript became the core of my second popular physics book *An Old Man's Toy*. Before long, I found parts of *Fearful Symmetry* excerpted in a college textbook on writing and received invitations to speak to classes on creative writing.

I am not happy that Macmillan Publishing Company allowed my book to go out of print. I have subsequently been acquainted with some horrifying statistics about the commercial publishing industry. So I am truly happy, particularly as an alumnus of Princeton University, that Princeton University Press is publishing a new edition of *Fearful Symmetry*. I thank the physicists Murph Goldberger, Dave Spergel, and Sam Treiman for encouraging this project, and my editors Trevor Lipscombe and Donna Kronemeyer for their good work.

I would like to thank Joe Polchinski and Roger Shepard for reading the Afterword added for this Princeton University edition. I think it appropriate to thank once again the physicists who read parts or all of the original manuscript: Bill Bialek, Sidney Coleman, Murray Gell-Mann, Tsung-dao Lee, Heinz Pagels, Steve Weinberg, and Frank Wilczek. Finally, I must thank Gretchen Zee for her years of support and love.

Santa Barbara
March 1999

Preface

In *Fearful Symmetry,* I wish to discuss the aesthetic motivations that animate twentieth-century physics. I am interested more in conveying to the reader a sense of the intellectual framework within which fundamental physics operates and less in explaining the factual content of modern physics.

Albert Einstein once said, "I want to know how God created this world. I am not interested in this or that phenomenon, in the spectrum of this and that element. I want to know His thoughts, the rest are details."

As a physicist, I am much enamored of the sentiment expressed by Einstein. While the vast majority of contemporary physicists are engaged in explaining specific phenomena, and rightly so, a small group, the intellectual descendants of Einstein, have become more ambitious. They have entered the forest of the night in search of the fundamental design of Nature and, in their limitless hubris, have claimed to have glimpsed it.

Two great principles guide this search: symmetry and renormalizability. Renormalizability refers to how physical processes with different characteristic lengths are related to each other. While I will touch on renormalizability, my focus will be on symmetry as the unifying aesthetic viewpoint through which fundamental physicists look at Nature.

There has been a growing interest in modern physics over the last few years. Expositions of the "new" physics abound. By now many of us have learned that there are billions and billions of galaxies, each containing billions and billions of stars. We have been told that the world may be understood in terms of subnuclear particles, most of which live for a billionth of a billionth of a second. The informed reader has been astounded and dazzled. Yes, indeed, the world of modern physics is wonderfully bizarre. Particles carrying Greek names jitterbug to the music of the quantum in defiance of classical determinism. But ultimately, the reader may come away with a sense of being fed simply the facts which, while truly amazing, become tiresome of themselves.

This book is addressed to the intellectually curious reader who wants to go beyond the facts. I have a mental image of that reader: someone I once knew in my youth; someone who may have since become an architect, an artist, a dancer, a stockbroker, a biologist, or a lawyer; someone who is interested in the intellectual and aesthetic framework within which fundamental physicists operate.

This does not mean that the astounding discoveries of modern physics will not be explained in this book. They will have to be explained before I can meaningfully discuss the intellectual framework of modern physics. I hope, however, that the reader will come away with not only a nodding acquaintance with certain astounding facts, but also with a sense of the framework without which they would remain, simply, facts.

I have not attempted to give a detailed and balanced history of symmetry in physics. Any account in which major developments are attributed to a handful of individuals cannot claim to be history, and any assertion to that effect must be rejected categorically. In speaking of certain developments in modern particle physics, the eminent physicist Shelley Glashow once remarked: "Tapestries are made by many artisans working together. The contributions of separate workers cannot be discerned in the completed work, and the loose and false threads have been covered over. So it is in our picture of particle physics. . . . [The standard theory] did not arise full blown in the mind of one physicist, nor even of three. It, too, is the result of the collective endeavor of many scientists, both experimenters and theorists." And yet, in a popular account such as this I am forced, inevitably, to simplify history. I trust that the reader understands.

—Santa Barbara, April 1986

Acknowledgments

First and foremost, I would like to thank my wife, Gretchen. Her incisive and critical comments, as well as her loving support, were essential. She would read each chapter as I went along, brutally slashing through the typescript. "I can't understand this!" she would scrawl across the page. And back to the writing-board I would go.

Our friends Kim Beeler, Chris Groesbeck, Martha and Frank Retman, and Diane Shuford—a psychologist, a student of art history, a lawyer, and two architects between them—read various portions of the manuscript to ensure that the text would be understandable to the lay reader.

Heinz Pagels and Steve Weinberg, two distinguished colleagues who have published popular books on physics, both encouraged me to pursue my idea of writing one about symmetry. They generously advised me on various aspects of writing and publishing, and introduced me to their friends in the publishing world.

I am grateful to Tsung-dao Lee, Heinz Pagels, and Steve Weinberg for reading the manuscript, and for their helpful and encouraging comments. I would also like to thank Sidney Coleman and Frank Wilczek for reading Chapter 12, Murray Gell-Mann for reading Chapter 11, and Bill Bialek for reading the galley proofs.

I am fortunate to have Charles Levine as my editor. His advice and support were indispensable. He was reassuring when I needed reassurance and critical when I needed criticism. I have come to value him as a friend.

My line editor, Catherine Shaw, clearly did a good job since I had to spend nearly two months rewriting the manuscript to answer all her comments. "I can't understand this!" she would exclaim in her turn. The book became clearer as a result. The manuscript was further smoothed by my copy editor, Roberta Frost.

Martin Kessler offered helpful advice during the early stages of this project.

I have also benefited from the advice of my agents, John Brockman and Katinka Matson.

The artists listed below helped to make the book more visually appealing and clearer.

I am pleased that the design director for the book is Helen Mills, whose brother Robert we will meet in Chapter 12. An appreciation for symmetry and balance appears to run in the family.

Finally, I would like to thank Debra Witmoyer, Lisa Lopez, Gwen Cattron, Katie Doremus, Karen Murphy, and Kresha Warnock for typing various portions of the manuscript.

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I

SYMMETRY AND DESIGN

1

In Search of Beauty

> What I remember most clearly was that when I put down a suggestion that seemed to me cogent and reasonable, Einstein did not in the least contest this, but he only said, "Oh, how ugly." As soon as an equation seemed to him to be ugly, he really rather lost interest in it and could not understand why somebody else was willing to spend much time on it. He was quite convinced that beauty was a guiding principle in the search for important results in theoretical physics.
> —H. Bondi

BEAUTY BEFORE TRUTH

My colleagues and I in fundamental physics are the intellectual descendants of Albert Einstein; we like to think that we too search for beauty. Some physics equations are so ugly that we cannot bear to look at them, let alone write them down. Certainly, the Ultimate Designer would use only beautiful equations in designing the universe! we proclaim. When presented with two alternative equations purporting to describe Nature, we always choose the one that appeals to our aesthetic sense. "Let us worry about beauty first, and truth will take care of itself!" Such is the rallying cry of fundamental physicists.

The reader may perhaps think of physics as a precise and predictive science and not as a subject fit for aesthetic contemplation. But, in fact, aesthetics has become a driving force in contemporary physics. Physicists have discovered something of wonder: Nature, at the fundamental level, is beautifully designed. It is this sense of wonder that I wish to share with you.

TRAINING OUR EYES

What is beauty? Philosophers pondering the meaning of aesthetics have produced weighty tomes, but an absolute definition of aesthetic values remains elusive. For one thing, fashion changes. The well-endowed ladies of Rubens no longer grace magazine covers. Aesthetic perceptions differ from culture to culture. Different conventions govern landscape painting in the East and West. The architectural designs of Bramante and I. M. Pei are beautiful in different ways. If there is no objective standard of beauty in the world of human creations, what system of aesthetics are we to use in speaking of the beauty of Nature? How are we to judge Nature's design?

In this book, I wish to explain how the aesthetic imperatives of contemporary physics make up a system of aesthetics that can be rigorously formulated. As my art history professors used to say, one has "to train one's eyes." To the architectural cognoscenti, the same principles that guide the Renaissance architect guide the postmodern. Likewise, physicists have to train their inner eye to see the universal principles guiding Nature's design.

INTRINSIC VERSUS EXTRINSIC BEAUTY

When I find a chambered nautilus at the seashore (or more likely in a shellshop), its beauty captivates me. But a developmental biologist would tell me that the perfect spiral is merely a consequence of unequal rate of shell growth. As a human being, I am no less enthralled by the beautiful nautilus knowing this fact, but as a physicist, I am driven to go beyond the extrinsic beauty that we can see. I want to discuss the beauty of neither the crashing wave nor the rainbow arcing across the sky, but the more profound beauty embodied in the physical laws that ultimately govern the behavior of water in its various forms.

LIVING IN A DESIGNER UNIVERSE

Physicists from Einstein on have been awed by the profound fact that, as we examine Nature on deeper and deeper levels, She appears ever more beautiful. Why should that be? We could have found ourselves living in an intrinsically ugly universe, a "chaotic world," as Einstein put it, "in no way graspable through thinking."

Musing along these lines often awakens feelings in physi-

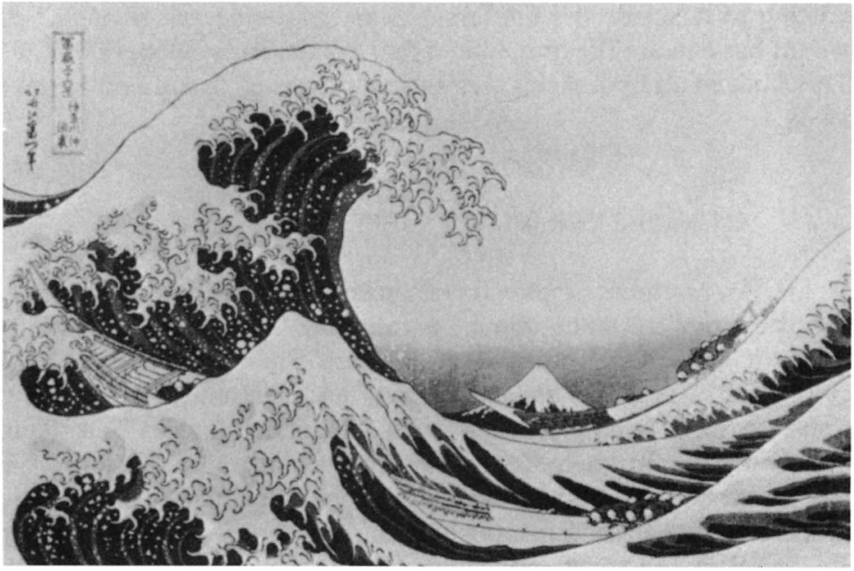

Figure 1.1. *(Top)* Hokusai (1760–1849) "Mount Fuji Seen from Kanagawa." *(Courtesy Minneapolis Institute of Art)*
(Bottom) Microphotograph of a snowflake *(R. B. Hoit, courtesy Photo Researchers, Inc.)*
The beauty of water on two different levels.

cists best described as religious. In judging a physical theory purporting to describe the universe, Einstein would ask himself if he would have made the universe in that particular way, were he God. This faith in an underlying design has sustained fundamental physicists.

THE MUSIC VERSUS THE LIBRETTO

Popularizers of physics often regale us with descriptions of specific physical phenomena, astounding their readers with the fantastic discoveries of modern physics. I am more interested in conveying a sense of the intellectual and aesthetic framework of contemporary fundamental physics. Consider opera. The aficionado likes *Turandot*, but not primarily because of its libretto. The absurd story takes flight because of Puccini's music. On the other hand, it would be difficult to sit through an opera without knowing the story or worse yet, to listen only to the orchestral part. The music and libretto inform each other.

Similarly, to speak of the multitude of specific physical phenomena (the libretto) without placing them in the aesthetic framework of contemporary physics (the music) is boring and not particularly enlightening. I intend to give the reader the music of modern physics—the aesthetic imperatives that guide physicists. But just as an opera with the vocal part taken out would be senseless, a discussion of aesthetics without reference to actual physical phenomena is sterile. I will have to go through the libretto of physics. Ultimately, however, both as a fundamental physicist and as an opera lover, I must confess that my heart lies more with the music, and not the libretto.

LOCAL ORDINANCES VERSUS CONSTITUTIONAL PRINCIPLES

In a book about physics, the much-abused phrase "physical law" is certain to be bandied about. In civil law, one distinguishes between local ordinances and constitutional principles. So too in physics, there are laws and there are laws. Consider Hooke's law, stating that the force required to stretch a metal spring is proportional to the amount by which that spring is stretched. It is an example of a phenomenological law, a concise statement of an empirically observed regularity. In the 1930s, the theory of metals was worked out, and Hooke's law was explained in terms of the electromagnetic interaction between the atoms in a metal. Hooke's law addresses one specific phenomenon. In contrast, an understanding of fundamental laws governing electromagnetism enables us to explain a bewildering variety of phenomena.

When I was learning about such things as Hooke's law in high school, I got the impression that physicists try to find as many laws as possible, to explain every single phenomenon observed in the physical world. In fact, my colleagues and I in fundamental physics are working toward having as few laws as possible. The ambition of fundamental physics is to replace the multitude of phenomenological laws with a single fundamental law, so as to arrive at a unified description of Nature. This drive toward unity is *Fearful Symmetry*'s central theme.

2

Symmetry and Simplicity

> I want to know how God created this world. I am not interested in this or that phenomenon, in the spectrum of this or that element. I want to know His thoughts, the rest are details.
> —A. Einstein

A GLIMPSE OF NATURE

Suppose an architect wakes up to find himself imprisoned in a strange room. He rushes to a window to look out. He can glimpse a tower here, a column there: Evidently, he is in an enormous mansion. Soon, professional fascination overtakes the architect's fears. What he is able to see is beautiful. He is obsessed and challenged; starting with what he has glimpsed, he wants to deduce the underlying design of the mansion. Is the mansion's designer a madman who piled complexity upon complexity? Did he stick a wing here, a pediment there, without rhyme or reason? Is he a hack architect? The architect-prisoner is sustained by an inexplicable faith that the foremost architect in the world has designed the mansion based on an elegantly simple and unifying principle.

We, too, wake to find ourselves in a strangely beautiful universe. The sheer splendor and wealth of physical phenomena never fail to astonish us. As physics progressed, physicists discovered that the diversity of phenomena did not require a diversity of explanations. In this century physicists have become increasingly ambitious. They have witnessed the incessant dance of the quantum and glimpsed the eternal secrets of space and time. No longer content to explain this phenomenon or that, they have become imbued with the faith that Nature has an underlying design of beautiful simplicity. Since Einstein, this faith in the ultimate comprehensibility of the world has sustained them.

Fundamental physics progresses in spurts. Understanding that has accumulated slowly is suddenly synthesized, and the entire outlook of the field shifts. The invention of quantum physics in the 1920s furnishes a dramatic example. The years following 1971 will also likely come to be regarded as one of those spurts of feverish creativity from which deeper understanding emerges. In their exhilaration and unlimited hubris, some physicists have even gone so far as to suggest that we now have glimpsed the ultimate design of Nature, a claim that we will examine.

This glimpse reveals one astonishing fact: Nature's underlying design appears beautifully simple. Einstein was right.

AN AUSTERE BEAUTY

The term "beauty" is loaded with connotations. In everyday experience our perception of beauty is tied to the psychological, the cultural, the social, and, often even the biological. Evidently, that kind of beauty does not lie at the heart of physics.

The beauty that Nature has revealed to physicists in Her laws is a beauty of design, a beauty that recalls, to some extent, the beauty of classical architecture, with its emphasis on geometry and symmetry. The system of aesthetics used by physicists in judging Nature also draws its inspiration from the austere finality of geometry.

Picture a circle, a square, and a rectangle. Quick, which one is more pleasing to the eye? Following the ancient Greeks, most people will probably choose the circle. To be sure, the square, even the rectangle, is not without passionate admirers. But there is an objective criterion that ranks the three, circle, square, rectangle, in that order: The circle possesses more symmetry.

Perhaps I should not ask which geometrical figure is more beautiful, but which is more symmetrical. But again, following the ancient Greeks, who waxed eloquent on the perfect beauty of spheres and the celestial music they make, I will continue to equate symmetry with beauty.

The precise mathematical definition of symmetry involves the notion of invariance. A geometrical figure is said to be symmetric under certain operations if those operations leave it unchanged. For example, the circle is left invariant by rotations around its center. Considered as an abstract entity, the circle is unchanged, whether we rotate it through 17° or any other angle. The square, in contrast, is left unchanged only by rotations around its center through angles of 90°, 180°, 270°, and 360°. (As far as its effect on geometrical figures is concerned, a rotation through 360° is equivalent, of course, to a rotation through 0°, or no rotation at all.) The rectangle is even less symmetric than the square. It is left invariant only by rotations around its center through angles of 180° and 360°.

Besides rotations, reflections also leave these simple geometrical figures invariant. Once again, the circle is more symmetric; it is left invariant by reflections across any straight line that passes through its center.

There is an alternative, but equivalent, formulation of the notion of symmetry that is more convenient for physics. Instead of rotating a given geometrical figure, one can ask whether the figure appears the same to two observers whose viewpoints are rotated from each other. Obviously, if I tilt my head 17°, the square will look tilted but the circle will look the same.

THE BEAVER'S LESSON

You boil it in sawdust:
You salt it in glue:
You condense it with locusts in tape:
Still keeping one principal object in view—
To preserve its symmetrical shape.
—Lewis Carroll, "The Beaver's Lesson" in *The Hunting of the Snark*

In geometry, it is entirely natural to ask what one can do to a geometrical object without changing it. But physicists do not deal with geometrical figures. So how, then, does symmetry enter into physics?

Following the geometer, the physicist might want to ask what one can "do" to physical reality without changing it. This is clearly not quite the right question, but it suggests one of the basic concerns of physics: Does physical reality appear different as perceived by different physicists with different viewpoints?

Consider two physicists. Suppose one of them, for some nutty reason, always looks at the world with his head tilted 31° from the vertical, while the other takes the more conventional view. After years of study, the two separately summarize their observations in several physical laws. Finally, they compare notes.

Figure 2.1. An artist's conception of the beaver's lesson.

We say that a physical law is invariant under rotation by 31° if they agree on that law. The nutty physicist now tilts his head to some other angle and resumes his study of the world. Eventually, the two physicists come to suspect that they agree regardless of the angle that separates their viewpoints. Real-life physicists have also come to believe that physical laws are invariant under rotation by any angle. Physics is said to have rotational symmetry.

ROTATIONAL SYMMETRY

Historically, physicists first became aware of the symmetries of rotation and reflection—the symmetries associated with the space we actually live in. In the next chapter, I will tell the strange story of reflection symmetry. Here, I will discuss rotational symmetry as a particularly simple and intuitively accessible example of a physical symmetry.

I have given a somewhat long, but precise definition of rotational symmetry: If we rotate our viewpoint, physical reality remains the same. The intellectual precision of our definition of rotational symmetry is necessary lest we make the same mistake as the ancient Greeks. I could have simply said that physical reality is perfect, like a circle or a sphere. Indeed, this vague but striking

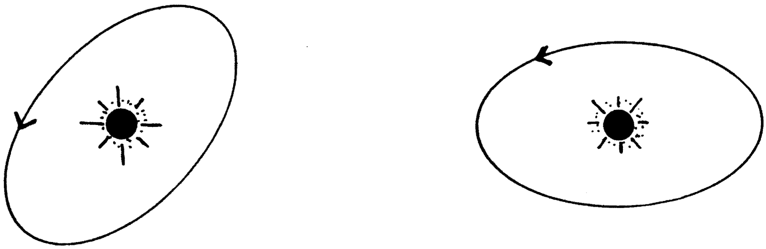

Figure 2.2. In classical physics, rotational symmetry merely tells us that if we rotate a planetary system through any angle we choose, the rotated orbit is also a possible orbit. The ancient Greeks thought erroneously that rotational symmetry implies a circular orbit.

statement more or less paraphrases what the ancients believed, the sort of statement that lured them into the fallacious conclusion that the orbits of the planets must be circles. The correct definition of rotational symmetry does not require circular orbits at all.

Evidently, to say that physics has rotational symmetry is to say that it does not pick out a special direction in space. To the modern rational mind, particularly the mind entertained by films of intergalactic warfare, the statement that no one direction is intrinsically preferable to another is almost a matter of philosophical necessity. It seems absurd to point to some direction and say that *that* direction is special. But, in fact, not long ago everybody believed precisely that. For eons, human perception of the physical world was dominated totally by gravity, and the realization that the terms "up" and "down" had no intrinsic significance came as an astounding discovery. Though Eratosthenes in ancient Greece suspected that the earth was round, our understanding of rotational symmetry really started with Newton's insight that apples do not fall down to earth, but rather toward the center of the earth.

It goes without saying that physics is founded on empiricism and that rotational symmetry can only be established by experiment. In the 1930s, the Hungarian-American physicist Eugene Wigner worked out the observable consequences of rotational symmetry applied to quantum phenomena, such as the emission of light by an atom. No, experimentalists do not actually tilt their heads. They achieve the same effect, instead, by placing several light detectors around light-emitting atoms. The rates at which the various detectors register the arrival of light are monitored and compared with the theoretical rate Wigner predicted using rotational symmetry.

Thus far, experiments have always upheld rotational invariance. If tomorrow's newspaper were to report the fall of this cherished symmetry, physicists would be shocked out of their minds. At issue would be nothing less than our fundamental conception of space.

We intuitively know space to be a smooth continuum, an arena in which the fundamental particles move and interact. This assumption underpins our physical theories, and no experimental evidence has ever contradicted it. However, the possibility that space may not be smooth cannot be excluded. A piece of silver looks perfectly smooth and structureless to the eye, but on closer inspection, we see a latticework of atoms. Is space itself a lattice? Our experimental probes simply may not have been fine enough to detect any graininess to space itself.

Thus, physicists developed the notion of symmetry as an objective criterion in judging Nature's design. Given two theories, physicists feel that the more symmetrical one, generally, is the more beautiful. When the beholder is a physicist, beauty *means* symmetry.

SYMMETRY OF PHYSICAL LAWS

It is crucial to distinguish between the symmetry of physical laws and the symmetry imposed by a specific situation. For example, physics students, traditionally, are made to work out the propagation of electromagnetic waves down a cylindrical metal pipe. While the laws of electromagnetism possess rotational symmetry, the problem obviously has only cylindrical symmetry: The axis of the pipe defines a direction in space. Physicists studying specific phenomena generally are more aware of the symmetry imposed by physical situations than of the intrinsic symmetry of the physical laws. In contrast, in this book we are interested in the symmetry of fundamental laws. To underscore the point, let me give another example. In watching an apple fall, the fundamental physicist is interested in the fact that the law of gravity does not pick out any special direction, rather the fact that the earth is nearly spherical. The earth could be shaped like an eggplant, for all the physicist cares.

This distinction between the symmetry of physical laws and the symmetry imposed by a specific situation was one of Newton's great intellectual achievements, and it enabled physics as we know it to take shape. While this distinction, once spelled out, is fairly obvious, it is easy to get confused since in everyday usage we invariably mean by symmetry the symmetry of specific situations. When we say a painting displays a certain symmetry, we refer to the symmetry in the artist's arrangement of the pigments, which has nothing to do, of course, with the symmetry of the physical laws governing the pigment molecules. In this book, I try to explain abstract concepts by analogies involving concrete objects. The reader must keep in mind that we are always interested in the symmetry of the physical laws rather than the symmetry of concrete objects.

SPRING REDUX

In introducing this chapter, I said that physicists have glimpsed both beauty and simplicity in Nature's design. What do physicists mean by simplicity?

In its drive toward simplicity, the march of physics has been relentlessly reductionistic. Physics is possible because complicated phenomena can be reduced to their essentials.

Historically, for physics to progress, many *why* questions had to be reexpressed as *hows*. "Why does a stone accelerate as it falls?" The ancients thought that the stone, like a horse, is eager to return home. Physics began when Galileo, instead of asking why the stone fell, went out and measured how.

As children we are full of whys. But every answered why is replaced by another why. "Why are leaves so pleasantly green in the spring?" Well, the professor explains, leaves contain the chlorophyll molecule, a complicated assemblage of atoms that interacts with light waves in a complex way. The chlorophyll molecule absorbs most of the light, but not those components the human eye perceives as green. The explanation bores the typical layman (and nowadays, many physicists as well). Ultimately, the explanation to this question, and to numerous others like it, boils down to how the electron interacts with the fundamental particle of light, the photon.

Physicists began the modern theory of the interaction between electron and photon around 1928 and completed it by the early 1950s. How the electron interacts with the photon has been thoroughly understood for more than thirty years, and yet, one can't help but wonder why these two fundamental particles interact in the rather peculiar fashion that they do. This question, too, has been answered. Physicists know now that the electron-photon interaction is completely fixed by a symmetry principle, known as the gauge principle, which plays a pervasive role in Nature. Evidently, physicists can now insist on asking why Nature should respect the gauge principle. Here contemporary physics stops, and any discussion on this question, which amounts essentially to asking why there is light, dissolves into a haze of speculation.

While whys have been replaced by other whys, enormous progress has been made: One why replaces many whys. The theory of electron-photon interaction enables us to explain not only the verdure of spring, but also the stretching of springs, not to mention the behavior of lasers and transistors. In fact, almost all the physical phenomena of which we are directly aware may be explained by the interaction between photons and electrons.

Physics is the most reductionistic of sciences. In contrast, the explanations that I have read in popular expositions of biology, although fascinating, have been emphatically nonreductionistic. Often, the explanations in terms of biochemical processes are more complicated than the phenomena in question.

Contemporary physics rests on the cornerstone of reductionism. As we delve deeper, Nature appears ever simpler. That this is so is, in fact, astonishing. We have no a priori reason to expect the universe, with its fantastic wealth of bewilderingly complex phenomena, to be governed ultimately by a few simple rules.

SIMPLICITY BEGETS COMPLEXITY

Let the next contest for the Prix de Rome for architects ask for a design of the universe. Asked to design the universe, many would be tempted to overdesign, to make things complicated so that their universe would display an interesting variety of phenomena.

It is easy to produce complicated behavior with a complicated design. As children, when we take apart a complicated mechanical toy, we expect to find a maze of cogs and wheels hidden

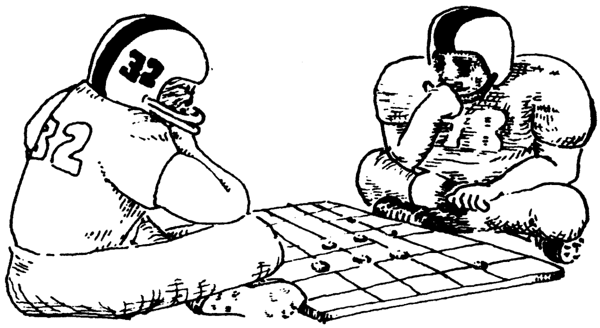

Figure 2.3. Football has complicated rules, the game of Go exceedingly simple ones.

inside. The American game of football is my favorite sport to watch, because of the variety of behavior exhibited. But the complex repertoire is the direct result of probably the most complicated set of rules in sports. Similarly, the complexity of chess is generated by its rather complicated rules.

Nature, whose complexity emerges from simplicity, is cleverer. One might say that the workings of the universe are more like the oriental game of Go than chess or football. The rules of Go can be stated simply and yet give rise to complex patterns. The eminent physicist Shelley Glashow has likened contemporary physicists to kibitzers at a game whose rules they do not know. But by watching long and hard, the kibitzers begin to guess what the rules might be.

As glimpsed by physicists, Nature's rules are simple, but also intricate: Different rules are subtly related to each other. The intricate relations between the rules produce interesting effects in many physical situations.

In the United States, a committee of the National Football League meets every year to review the past season and to tinker with the rules. As every observer of the sport knows, an apparently insignificant change in even one rule can drastically affect the pattern of the game. Restrict slightly how a cornerback can bump a receiver and the game becomes offense dominated. Over the years, the rules of the game have evolved to ensure an interesting balance between offense and defense. Similarly, Nature's laws appear to be delicately balanced.

An example of this balance occurs in the evolution of stars.

A typical star starts out as a gas of protons and electrons. Under the effect of gravity, the gas eventually condenses into a spherical blob in which nuclear and electric forces stage a mighty contest. The reader might recall that the electric force is such that like charges repel each other. Protons are kept apart, therefore, by their mutual electric repulsion. On the other hand, the nuclear attraction between protons tries to bring them together. In this struggle the electric force has a slight edge, a fact of great importance to us. Were the nuclear attraction between protons a tiny bit stronger, two protons could get stuck together, thus releasing energy. Nuclear reactions would then occur very rapidly, burning out the nuclear fuel of stars in a short time, thereby making steady stellar evolution, let alone civilization, impossible. In fact, the nuclear force is barely strong enough to glue a proton and a neutron together, but not strong enough to glue two protons together. Roughly speaking, before a proton can interact with another proton, it first has to transform itself into a neutron. This transformation is effected by what is known as the weak interaction. Processes effected by the weak interaction occur very slowly, as the term "weak" suggests. As a result, nuclear burning in a typical star like the sun occurs at a stately pace, bathing us in a steady, warm glow.

The central point is that, unlike the rules of football, Nature's rules are not arbitrary; they are dictated by the same general principle of symmetry and linked together in an organic whole.

Nature's design is not only simple, but minimally so, in the sense that were the design any simpler, the universe would be a much duller place. Theoretical physicists sometimes amuse themselves by imagining what the universe would be like if the design were less symmetric. These mental exercises show that not a stone can be disturbed lest the entire edifice crumble. For instance, light might disappear from the universe, and that would be no fun at all.

THE RULE OF LARGE NUMBERS

One reason that an underlying simplicity can generate complicated phenomena is the occurrence in Nature of ridiculously large numbers. A drop of water contains a mind-boggling number of atoms. Young children are fascinated by large numbers and are delighted when taught words like "thousand" and "million." They