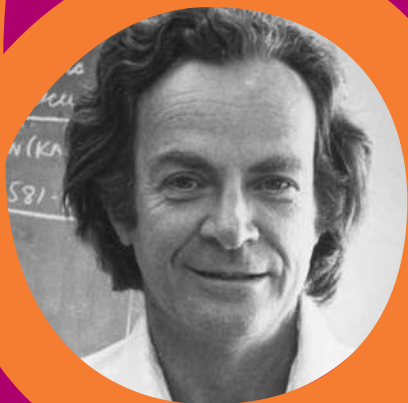


"The most original mind of his generation." —FREEMAN DYSON

# RICHARD P. FEYNMAN

## SIX EASY PIECES



ESSENTIALS OF PHYSICS  
EXPLAINED BY ITS MOST  
BRILLIANT TEACHER

# SIX EASY PIECES

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(with Ralph Leighton)

# SIX EASY PIECES

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Essentials of Physics Explained  
by Its Most Brilliant Teacher

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RICHARD P. FEYNMAN

*with*

Robert B. Leighton

*and*

Matthew Sands

*Introduction by*

Paul Davies

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## PUBLISHER'S NOTE

*Six Easy Pieces* grew out of the need to bring to as wide an audience as possible a substantial yet nontechnical physics primer based on the science of Richard Feynman. We have chosen the six easiest chapters from Feynman's celebrated and landmark text, *The Feynman Lectures on Physics* (originally published in 1963), which remains his most famous publication. General readers are fortunate that Feynman chose to present certain key topics in largely qualitative terms without formal mathematics, and these are brought together for *Six Easy Pieces*.

We would like to thank Paul Davies for his insightful introduction to this newly formed collection. Following his introduction we have chosen to reproduce two prefaces from *The Feynman Lectures on Physics*, one by Feynman himself and one by two of his colleagues, because they provide context for the pieces that follow and insight into both Richard Feynman and his science.

Finally, we would like to thank the California Institute of Technology's Physics Department and Institute Archives, in particular Dr. Judith Goodstein, and Dr. Brian Hatfield, for his outstanding advice and recommendations throughout the development of this project.





# INTRODUCTION

There is a popular misconception that science is an impersonal, dispassionate, and thoroughly objective enterprise. Whereas most other human activities are dominated by fashions, fads, and personalities, science is supposed to be constrained by agreed rules of procedure and rigorous tests. It is the results that count, not the people who produce them.

This is, of course, manifest nonsense. Science is a people-driven activity like all human endeavor, and just as subject to fashion and whim. In this case fashion is set not so much by choice of subject matter, but by the way scientists think about the world. Each age adopts its particular approach to scientific problems, usually following the trail blazed by certain dominant figures who both set the agenda and define the best methods to tackle it. Occasionally scientists attain sufficient stature that they become noticed by the general public, and when endowed with outstanding flair a scientist may become an icon for the entire scientific community. In earlier centuries Isaac Newton was an icon. Newton personified the gentleman scientist—well connected, devoutly religious, unhurried, and methodical in his work. His style of doing science set the standard for two hundred years. In the first half of the twentieth century Albert Einstein replaced Newton as the popular scientist icon. Eccentric, dishevelled, Germanic, absent-minded, utterly absorbed in his work, and an archetypal abstract thinker, Einstein changed the way that physics is done by questioning the very concepts that define the subject.

Richard Feynman has become an icon for late twentieth-century

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physics—the first American to achieve this status. Born in New York in 1918 and educated on the East Coast, he was too late to participate in the Golden Age of physics, which, in the first three decades of this century, transformed our worldview with the twin revolutions of the theory of relativity and quantum mechanics. These sweeping developments laid the foundations of the edifice we now call the New Physics. Feynman started with those foundations and helped build the ground floor of the New Physics. His contributions touched almost every corner of the subject and have had a deep and abiding influence over the way that physicists think about the physical universe.

Feynman was a theoretical physicist par excellence. Newton had been both experimentalist and theorist in equal measure. Einstein was quite simply contemptuous of experiment, preferring to put his faith in pure thought. Feynman was driven to develop a deep theoretical understanding of nature, but he always remained close to the real and often grubby world of experimental results. Nobody who watched the elderly Feynman elucidate the cause of the Challenger space shuttle disaster by dipping an elastic band in ice water could doubt that here was both a showman and a very practical thinker.

Initially, Feynman made a name for himself from his work on the theory of subatomic particles, specifically the topic known as quantum electrodynamics or QED. In fact, the quantum theory began with this topic. In 1900, the German physicist Max Planck proposed that light and other electromagnetic radiation, which had hitherto been regarded as waves, paradoxically behaved like tiny packets of energy, or “quanta,” when interacting with matter. These particular quanta became known as photons. By the early 1930s the architects of the new quantum mechanics had worked out a mathematical scheme to describe the emission and absorption of photons by electrically charged particles such as electrons. Although this early formulation of QED enjoyed some limited success, the theory was clearly flawed. In many cases calculations gave inconsistent and even infinite answers to well-posed physical questions.

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It was to the problem of constructing a consistent theory of QED that the young Feynman turned his attention in the late 1940s.

To place QED on a sound basis it was necessary to make the theory consistent not only with the principles of quantum mechanics but with those of the special theory of relativity too. These two theories come with their own distinctive mathematical machinery, complicated systems of equations that can indeed be combined and reconciled to yield a satisfactory description of QED. Doing this was a tough undertaking, requiring a high degree of mathematical skill, and was the approach followed by Feynman's contemporaries. Feynman himself, however, took a radically different route—so radical, in fact, that he was more or less able to write down the answers straightaway without using any mathematics!

To aid this extraordinary feat of intuition, Feynman invented a simple system of eponymous diagrams. Feynman diagrams are a symbolic but powerfully heuristic way of picturing what is going on when electrons, photons, and other particles interact with each other. These days Feynman diagrams are a routine aid to calculation, but in the early 1950s they marked a startling departure from the traditional way of doing theoretical physics.

The particular problem of constructing a consistent theory of quantum electrodynamics, although it was a milestone in the development of physics, was just the start. It was to define a distinctive Feynman style, a style destined to produce a string of important results from a broad range of topics in physical science. The Feynman style can best be described as a mixture of reverence and disrespect for received wisdom.

Physics is an exact science, and the existing body of knowledge, while incomplete, can't simply be shrugged aside. Feynman acquired a formidable grasp of the accepted principles of physics at a very young age, and he chose to work almost entirely on conventional problems. He was not the sort of genius to beaver away in isolation in a backwater of the discipline and to stumble across the profoundly new. His special talent was to approach essentially mainstream topics in an idiosyncratic way. This meant eschewing

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existing formalisms and developing his own highly intuitive approach. Whereas most theoretical physicists rely on careful mathematical calculation to provide a guide and a crutch to take them into unfamiliar territory, Feynman's attitude was almost cavalier. You get the impression that he could read nature like a book and simply report on what he found, without the tedium of complex analysis.

Indeed, in pursuing his interests in this manner Feynman displayed a healthy contempt for rigorous formalisms. It is hard to convey the depth of genius that is necessary to work like this. Theoretical physics is one of the toughest intellectual exercises, combining abstract concepts that defy visualization with extreme mathematical complexity. Only by adopting the highest standards of mental discipline can most physicists make progress. Yet Feynman appeared to ride roughshod over this strict code of practice and pluck new results like ready-made fruit from the Tree of Knowledge.

The Feynman style owed a great deal to the personality of the man. In his professional and private life he seemed to treat the world as a hugely entertaining game. The physical universe presented him with a fascinating series of puzzles and challenges, and so did his social environment. A lifelong prankster, he treated authority and the academic establishment with the same sort of disrespect he showed for stuffy mathematical formalism. Never one to suffer fools gladly, he broke the rules whenever he found them arbitrary or absurd. His autobiographical writings contain amusing stories of Feynman outwitting the atom-bomb security services during the war, Feynman cracking safes, Feynman disarming women with outrageously bold behavior. He treated his Nobel Prize, awarded for his work on QED, in a similar take-it-or-leave-it manner.

Alongside this distaste for formality, Feynman had a fascination with the quirky and obscure. Many will remember his obsession with the long-lost country of Tuva in Central Asia, captured so delightfully in a documentary film made near the time of his death.

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His other passions included playing the bongo drums, painting, frequenting strip clubs, and deciphering Mayan texts.

Feynman himself did much to cultivate his distinctive persona. Although reluctant to put pen to paper, he was voluble in conversation, and loved to tell stories about his ideas and escapades. These anecdotes, accumulated over the years, helped add to his mystique and made him a proverbial legend in his own lifetime. His engaging manner endeared him greatly to students, especially the younger ones, many of whom idolized him. When Feynman died of cancer in 1988 the students at Caltech, where he had worked for most of his career, unfurled a banner with the simple message: “We love you Dick.”

It was Feynman’s happy-go-lucky approach to life in general and physics in particular that made him such a superb communicator. He had little time for formal lecturing or even for supervising Ph.D. students. Nevertheless he could give brilliant lectures when it suited him, deploying all the sparkling wit, penetrating insight, and irreverence that he brought to bear on his research work.

In the early 1960s Feynman was persuaded to teach an introductory physics course to Caltech freshmen and sophomores. He did so with characteristic panache and his inimitable blend of informality, zest, and offbeat humor. Fortunately, these priceless lectures were saved for posterity in book form. Though far removed in style and presentation from more conventional teaching texts, *The Feynman Lectures on Physics* were a huge success, and they excited and inspired a generation of students across the world. Three decades on, these volumes have lost nothing of their sparkle and lucidity. *Six Easy Pieces* is culled directly from *The Feynman Lectures on Physics*. It is intended to give general readers a substantive taste of Feynman the Educator by drawing on the early, nontechnical chapters from that landmark work. The result is a delightful volume—it serves both as a primer on physics for nonscientists and as a primer on Feynman himself.

What is most impressive about Feynman’s carefully crafted exposition is the way that he can develop far-reaching physical notions from the most slender investment in concepts, and a

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minimum in the way of mathematics and technical jargon. He has the knack of finding just the right analogy or everyday illustration to bring out the essence of a deep principle, without obscuring it in incidental or irrelevant details.

The selection of topics contained in this volume is not intended as a comprehensive survey of modern physics, but as a tantalizing taste of the Feynman approach. We soon discover how he can illuminate even mundane topics like force and motion with new insights. Key concepts are illustrated by examples drawn from daily life or antiquity. Physics is continually linked to other sciences while leaving the reader in no doubt about which is the fundamental discipline.

Right at the beginning of *Six Easy Pieces* we learn how all physics is rooted in the notion of law—the existence of an ordered universe that can be understood by the application of rational reasoning. However, the laws of physics are not transparent to us in our direct observations of nature. They are frustratingly hidden, subtly encoded in the phenomena we study. The arcane procedures of the physicist—a mixture of carefully designed experimentation and mathematical theorizing—are needed to unveil the underlying law-like reality.

Possibly the best-known law of physics is Newton's inverse square law of gravitation, discussed here in Chapter Five. The topic is introduced in the context of the solar system and Kepler's laws of planetary motion. But gravitation is universal, applying across the cosmos, enabling Feynman to spice his account with examples from astronomy and cosmology. Commenting on a picture of a globular cluster somehow held together by unseen forces, he waxes lyrical: "If one cannot see gravitation acting here, he has no soul."

Other laws are known that refer to the various nongravitational forces of nature that describe how particles of matter interact with each other. There is but a handful of these forces, and Feynman himself holds the considerable distinction of being one of the few scientists in history to discover a new law of physics, pertaining to the way that a weak nuclear force affects the behavior of certain subatomic particles.

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High-energy particle physics was the jewel in the crown of post-war science, at once awesome and glamorous, with its huge accelerator machines and seemingly unending list of newly discovered subatomic particles. Feynman's research was directed mostly toward making sense of the results of this enterprise. A great unifying theme among particle physicists has been the role of symmetry and conservation laws in bringing order to the subatomic zoo.

As it happens, many of the symmetries known to particle physicists were familiar already in classical physics. Chief among these are the symmetries that arise from the homogeneity of space and time. Take time: apart from cosmology, where the big bang marked the beginning of time, there is nothing in physics to distinguish one moment of time from the next. Physicists say that the world is "invariant under time translations," meaning that whether you take midnight or midday to be the zero of time in your measurements, it makes no difference to the description of physical phenomena. Physical processes do not depend on an absolute zero of time. It turns out that this symmetry under time translation directly implies one of the most basic, and also most useful, laws of physics: the law of conservation of energy. This law says that you can move energy around and change its form but you can't create or destroy it. Feynman makes this law crystal clear with his amusing story of Dennis the Menace who is always mischievously hiding his toy building blocks from his mother (Chapter Four).

The most challenging lecture in this volume is the last, which is an exposition on quantum physics. It is no exaggeration to say that quantum mechanics had dominated twentieth-century physics and is far and away the most successful scientific theory in existence. It is indispensable for understanding subatomic particles, atoms and nuclei, molecules and chemical bonding, the structure of solids, superconductors and superfluids, the electrical and thermal conductivity of metals and semiconductors, the structure of stars, and much else. It has practical applications ranging from the laser to the microchip. All this from a theory that at first sight—and second sight—looks absolutely crazy! Niels Bohr, one of the founders of



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quantum mechanics, once remarked that anybody who is not shocked by the theory hasn't understood it.

The problem is that quantum ideas strike at the very heart of what we might call commonsense reality. In particular, the idea that physical objects such as electrons or atoms enjoy an independent existence, with a complete set of physical properties at all times, is called into question. For example, an electron cannot have a position in space and a well-defined speed at the same moment. If you look for where an electron is located, you will find it at a place, and if you measure its speed you will obtain a definite answer, but you cannot make both observations at once. Nor is it meaningful to attribute definite yet unknown values for the position and speed to an electron in the absence of a complete set of observations.

This indeterminism in the very nature of atomic particles is encapsulated by Heisenberg's celebrated uncertainty principle. This puts strict limits on the precision with which properties such as position and speed can be simultaneously known. A sharp value for position smears the range of possible values of speed and vice versa. Quantum fuzziness shows up in the way electrons, photons, and other particles move. Certain experiments can reveal them taking definite paths through space, after the fashion of bullets following trajectories toward a target. But other experimental arrangements reveal that these entities can also behave like waves, showing characteristic patterns of diffraction and interference.

Feynman's masterly analysis of the famous "two-slit" experiment, which teases out the "shocking" wave-particle duality in its starkest form, has become a classic in the history of scientific exposition. With a few very simple ideas, Feynman manages to take the reader to the very heart of the quantum mystery, and leaves us dazzled by the paradoxical nature of reality that it exposes.

Although quantum mechanics had made the textbooks by the early 1930s, it is typical of Feynman that, as a young man, he preferred to refashion the theory for himself in an entirely new guise. The Feynman method has the virtue that it provides us with a vivid picture of nature's quantum trickery at work. The idea is that the

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path of a particle through space is not generally well defined in quantum mechanics. We can imagine a freely moving electron, say, not merely traveling in a straight line between A and B as common sense would suggest, but taking a variety of wiggly routes. Feynman invites us to imagine that somehow the electron explores all possible routes, and in the absence of an observation about which path is taken we must suppose that all these alternative paths somehow contribute to the reality. So when an electron arrives at a point in space—say a target screen—many different histories must be integrated together to create this one event.

Feynman's so-called path-integral, or sum-over-histories approach to quantum mechanics, set this remarkable concept out as a mathematical procedure. It remained more or less a curiosity for many years, but as physicists pushed quantum mechanics to its limits—applying it to gravitation and even cosmology—so the Feynman approach turned out to offer the best calculational tool for describing a quantum universe. History may well judge that, among his many outstanding contributions to physics, the path-integral formulation of quantum mechanics is the most significant.

Many of the ideas discussed in this volume are deeply philosophical. Yet Feynman had an abiding suspicion of philosophers. I once had occasion to tackle him about the nature of mathematics and the laws of physics, and whether abstract mathematical laws could be considered to enjoy an independent Platonic existence. He gave a spirited and skillful description of why this indeed appears so but soon backed off when I pressed him to take a specific philosophical position. He was similarly wary when I attempted to draw him out on the subject of reductionism. With hindsight, I believe that Feynman was not, after all, contemptuous of philosophical problems. But, just as he was able to do fine mathematical physics without systematic mathematics, so he produced some fine philosophical insights without systematic philosophy. It was formalism he disliked, not content.

It is unlikely that the world will see another Richard Feynman. He was very much a man of his time. The Feynman style worked

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well for a subject that was in the process of consolidating a revolution and embarking on the far-reaching exploration of its consequences. Postwar physics was secure in its foundations, mature in its theoretical structures, yet wide open for kibitzing exploitation. Feynman entered a wonderland of abstract concepts and imprinted his personal brand of thinking upon many of them. This book provides a unique glimpse into the mind of a remarkable human being.

*September 1994*

PAUL DAVIES

## SPECIAL PREFACE

(from *The Feynman Lectures on Physics*)

Toward the end of his life, Richard Feynman's fame had transcended the confines of the scientific community. His exploits as a member of the commission investigating the space shuttle *Challenger* disaster gave him widespread exposure; similarly, a best-selling book about his picaresque adventures made him a folk hero almost of the proportions of Albert Einstein. But back in 1961, even before his Nobel Prize increased his visibility to the general public, Feynman was more than merely famous among members of the scientific community—he was legendary. Undoubtedly, the extraordinary power of his teaching helped spread and enrich the legend of Richard Feynman.

He was a truly great teacher, perhaps the greatest of his era and ours. For Feynman, the lecture hall was a theater, and the lecturer a performer, responsible for providing drama and fireworks as well as facts and figures. He would prowling about the front of a classroom, arms waving, “the impossible combination of theoretical physicist and circus barker, all body motion and sound effects,” wrote *The New York Times*. Whether he addressed an audience of students, colleagues, or the general public, for those lucky enough to see Feynman lecture in person, the experience was usually unconventional and always unforgettable, like the man himself.

He was the master of high drama, adept at riveting the attention of every lecture-hall audience. Many years ago, he taught a course in Advanced Quantum Mechanics, a large class comprised of a few

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registered graduate students and most of the Caltech physics faculty. During one lecture, Feynman started explaining how to represent certain complicated integrals diagrammatically: time on this axis, space on that axis, wiggly line for this straight line, etc. Having described what is known to the world of physics as a Feynman diagram, he turned around to face the class, grinning wickedly. “And this is called *THE* diagram!” Feynman had reached the denouement, and the lecture hall erupted with spontaneous applause.

For many years after the lectures that make up this book were given, Feynman was an occasional guest lecturer for Caltech’s freshman physics course. Naturally, his appearances had to be kept secret so there would be room left in the hall for the registered students. At one such lecture the subject was curved-space time, and Feynman was characteristically brilliant. But the unforgettable moment came at the beginning of the lecture. The supernova of 1987 had just been discovered, and Feynman was very excited about it. He said, “Tycho Brahe had his supernova, and Kepler had his. Then there weren’t any for 400 years. But now I have mine.” The class fell silent, and Feynman continued on. “There are  $10^{11}$  stars in the galaxy. That used to be a *huge* number. But it’s only a hundred billion. It’s less than the national deficit! We used to call them astronomical numbers. Now we should call them economical numbers.” The class dissolved in laughter, and Feynman, having captured his audience, went on with his lecture.

Showmanship aside, Feynman’s pedagogical technique was simple. A summation of his teaching philosophy was found among his papers in the Caltech archives, in a note he had scribbled to himself while in Brazil in 1952:

First figure out why you want the students to learn the subject and what you want them to know, and the method will result more or less by common sense.

What came to Feynman by “common sense” were often brilliant twists that perfectly captured the essence of his point. Once, during

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a public lecture, he was trying to explain why one must not verify an idea using the same data that suggested the idea in the first place. Seeming to wander off the subject, Feynman began talking about license plates. “You know, the most amazing thing happened to me tonight. I was coming here, on the way to the lecture, and I came in through the parking lot. And you won’t believe what happened. I saw a car with the license plate ARW 357. Can you imagine? Of all the millions of license plates in the state, what was the chance that I would see that particular one tonight? Amazing!” A point that even many scientists fail to grasp was made clear through Feynman’s remarkable “common sense.”

In 35 years at Caltech (from 1952 to 1987), Feynman was listed as teacher of record for 34 courses. Twenty-five of them were advanced graduate courses, strictly limited to graduate students, unless undergraduates asked permission to take them (they often did, and permission was nearly always granted). The rest were mainly introductory graduate courses. Only once did Feynman teach courses purely for undergraduates, and that was the celebrated occasion in the academic years 1961 to 1962 and 1962 to 1963, with a brief reprise in 1964, when he gave the lectures that were to become *The Feynman Lectures on Physics*.

At the time there was a consensus at Caltech that freshman and sophomore students were getting turned off rather than spurred on by their two years of compulsory physics. To remedy the situation, Feynman was asked to design a series of lectures to be given to the students over the course of two years, first to freshmen, and then to the same class as sophomores. When he agreed, it was immediately decided that the lectures should be transcribed for publication. That job turned out to be far more difficult than anyone had imagined. Turning out publishable books required a tremendous amount of work on the part of his colleagues, as well as Feynman himself, who did the final editing of every chapter.

And the nuts and bolts of running a course had to be addressed. This task was greatly complicated by the fact that Feynman had only a vague outline of what he wanted to cover. This meant that

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no one knew what Feynman would say until he stood in front of a lecture hall filled with students and said it. The Caltech professors who assisted him would then scramble as best they could to handle mundane details, such as making up homework problems.

Why did Feynman devote more than two years to revolutionize the way beginning physics was taught? One can only speculate, but there were probably three basic reasons. One is that he loved to have an audience, and this gave him a bigger theater than he usually had in graduate courses. The second was that he genuinely cared about students, and he simply thought that teaching freshmen was an important thing to do. The third and perhaps most important reason was the sheer challenge of reformulating physics, as he understood it, so that it could be presented to young students. This was his specialty, and was the standard by which he measured whether something was really understood. Feynman was once asked by a Caltech faculty member to explain why spin  $1/2$  particles obey Fermi-Dirac statistics. He gauged his audience perfectly and said, "I'll prepare a freshman lecture on it." But a few days later he returned and said, "You know, I couldn't do it. I couldn't reduce it to the freshman level. That means we really don't understand it."

This specialty of reducing deep ideas to simple, understandable terms is evident throughout *The Feynman Lectures on Physics*, but nowhere more so than in his treatment of quantum mechanics. To aficionados, what he has done is clear. He has presented, to beginning students, the path integral method, the technique of his own devising that allowed him to solve some of the most profound problems in physics. His own work using path integrals, among other achievements, led to the 1965 Nobel Prize that he shared with Julian Schwinger and Sin-Itaro Tomanaga.

Through the distant veil of memory, many of the students and faculty attending the lectures have said that having two years of physics with Feynman was the experience of a lifetime. But that's not how it seemed at the time. Many of the students dreaded the class, and as the course wore on, attendance by the registered students started dropping alarmingly. But at the same time, more and

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more faculty and graduate students started attending. The room stayed full, and Feynman may never have known he was losing some of his intended audience. But even in Feynman's view, his pedagogical endeavor did not succeed. He wrote in the 1963 preface to the *Lectures*: "I don't think I did very well by the students." Rereading the books, one sometimes seems to catch Feynman looking over his shoulder, not at his young audience, but directly at his colleagues, saying, "Look at that! Look how I finessed that point! Wasn't that clever?" But even when he thought he was explaining things lucidly to freshmen or sophomores, it was not really they who were able to benefit most from what he was doing. It was his peers—scientists, physicists, and professors—who would be the main beneficiaries of his magnificent achievement, which was nothing less than to see physics through the fresh and dynamic perspective of Richard Feynman.

Feynman was more than a great teacher. His gift was that he was an extraordinary teacher of teachers. If the purpose in giving *The Feynman Lectures on Physics* was to prepare a roomful of undergraduate students to solve examination problems in physics, he cannot be said to have succeeded particularly well. Moreover, if the intent was for the books to serve as introductory college textbooks, he cannot be said to have achieved his goal. Nevertheless, the books have been translated into ten foreign languages and are available in four bilingual editions. Feynman himself believed that his most important contribution to physics would not be QED, or the theory of superfluid helium, or polarons, or partons. His foremost contribution would be the three red books of *The Feynman Lectures on Physics*. That belief fully justifies this commemorative issue of these celebrated books.

DAVID L. GOODSTEIN

GERRY NEUGEBAUER

California Institute of Technology

*April 1989*





## FEYNMAN'S PREFACE

(from *The Feynman Lectures on Physics*)

These are the lectures in physics that I gave last year and the year before to the freshman and sophomore classes at Caltech. The lectures are, of course, not verbatim—they have been edited, sometimes extensively and sometimes less so. The lectures form only part of the complete course. The whole group of 180 students gathered in a big lecture room twice a week to hear these lectures and then they broke up into small groups of 15 to 20 students in recitation sections under the guidance of a teaching assistant. In addition, there was a laboratory session once a week.

The special problem we tried to get at with these lectures was to maintain the interest of the very enthusiastic and rather smart students coming out of the high schools and into Caltech. They have heard a lot about how interesting and exciting physics is—the theory of relativity, quantum mechanics, and other modern ideas. By the end of two years of our previous course, many would be very discouraged because there were really very few grand, new, modern ideas presented to them. They were made to study inclined planes, electrostatics, and so forth, and after two years it was quite stultifying. The problem was whether or not we could make a course which would save the more advanced and excited student by maintaining his enthusiasm.

The lectures here are not in any way meant to be a survey course, but are very serious. I thought to address them to the most intelligent in the class and to make sure, if possible, that even the most

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*Feynman's Preface*

intelligent student was unable to completely encompass everything that was in the lectures—by putting in suggestions of applications of the ideas and concepts in various directions outside the main line of attack. For this reason, though, I tried very hard to make all the statements as accurate as possible, to point out in every case where the equations and ideas fitted into the body of physics, and how—when they learned more—things would be modified. I also felt that for such students it is important to indicate what it is that they should—if they are sufficiently clever—be able to understand by deduction from what has been said before, and what is being put in as something new. When new ideas came in, I would try either to deduce them if they were deducible, or to explain that it *was* a new idea which hadn't any basis in terms of things they had already learned and which was not supposed to be provable—but was just added in.

At the start of these lectures, I assumed that the students knew something when they came out of high school—such things as geometrical optics, simple chemistry ideas, and so on. I also didn't see that there was any reason to make the lectures in a definite order, in the sense that I would not be allowed to mention something until I was ready to discuss it in detail. There was a great deal of mention of things to come, without complete discussions. These more complete discussions would come later when the preparation became more advanced. Examples are the discussions of induction, and of energy levels, which are at first brought in in a very qualitative way and are later developed more completely.

At the same time that I was aiming at the more active student, I also wanted to take care of the fellow for whom the extra fireworks and side applications are merely disquieting and who cannot be expected to learn most of the material in the lecture at all. For such students, I wanted there to be at least a central core or backbone of material which he *could* get. Even if he didn't understand everything in a lecture, I hoped he wouldn't get nervous. I didn't expect him to understand everything, but only the central and most direct fea-

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tures. It takes, of course, a certain intelligence on his part to see which are the central theorems and central ideas, and which are the more advanced side issues and applications which he may understand only in later years.

In giving these lectures there was one serious difficulty: in the way the course was given, there wasn't any feedback from the students to the lecturer to indicate how well the lectures were going over. This is indeed a very serious difficulty, and I don't know how good the lectures really are. The whole thing was essentially an experiment. And if I did it again I wouldn't do it the same way—I hope I *don't* have to do it again! I think, though, that things worked out—so far as the physics is concerned—quite satisfactorily in the first year.

In the second year I was not so satisfied. In the first part of the course, dealing with electricity and magnetism, I couldn't think of any really unique or different way of doing it—of any way that would be particularly more exciting than the usual way of presenting it. So I don't think I did very much in the lectures on electricity and magnetism. At the end of the second year I had originally intended to go on, after the electricity and magnetism, by giving some more lectures on the properties of materials, but mainly to take up things like fundamental modes, solutions of the diffusion equation, vibrating systems, orthogonal functions, . . . developing the first stages of what are usually called “the mathematical methods of physics.” In retrospect, I think that if I were doing it again I would go back to that original idea. But since it was not planned that I would be giving these lectures again, it was suggested that it might be a good idea to try to give an introduction to the quantum mechanics—what you will find in Volume III.

It is perfectly clear that students who will major in physics can wait until their third year for quantum mechanics. On the other hand, the argument was made that many of the students in our course study physics as a background for their primary interest in other fields. And the usual way of dealing with quantum mechanics makes that subject almost unavailable for the great majority of

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students because they have to take so long to learn it. Yet, in its real applications—especially in its more complex applications, such as in electrical engineering and chemistry—the full machinery of the differential equation approach is not actually used. So I tried to describe the principles of quantum mechanics in a way which wouldn't require that one first know the mathematics of partial differential equations. Even for a physicist I think that is an interesting thing to try to do—to present quantum mechanics in this reverse fashion—for several reasons which may be apparent in the lectures themselves. However, I think that the experiment in the quantum mechanics part was not completely successful—in large part because I really did not have enough time at the end (I should, for instance, have had three or four more lectures in order to deal more completely with such matters as energy bands and the spatial dependence of amplitudes). Also, I had never presented the subject this way before, so the lack of feedback was particularly serious. I now believe the quantum mechanics should be given at a later time. Maybe I'll have a chance to do it again someday. Then I'll do it right.

The reason there are no lectures on how to solve problems is because there were recitation sections. Although I did put in three lectures in the first year on how to solve problems, they are not included here. Also there was a lecture on inertial guidance which certainly belongs after the lecture on rotating systems, but which was, unfortunately, omitted. The fifth and sixth lectures are actually due to Matthew Sands, as I was out of town.

The question, of course, is how well this experiment has succeeded. My own point of view—which, however, does not seem to be shared by most of the people who worked with the students—is pessimistic. I don't think I did very well by the students. When I look at the way the majority of the students handled the problems on the examinations, I think that the system is a failure. Of course, my friends point out to me that there were one or two dozen students who—very surprisingly—understood almost everything in all of the lectures, and who were quite active in working with the material and worrying about the many points in an excited and in-

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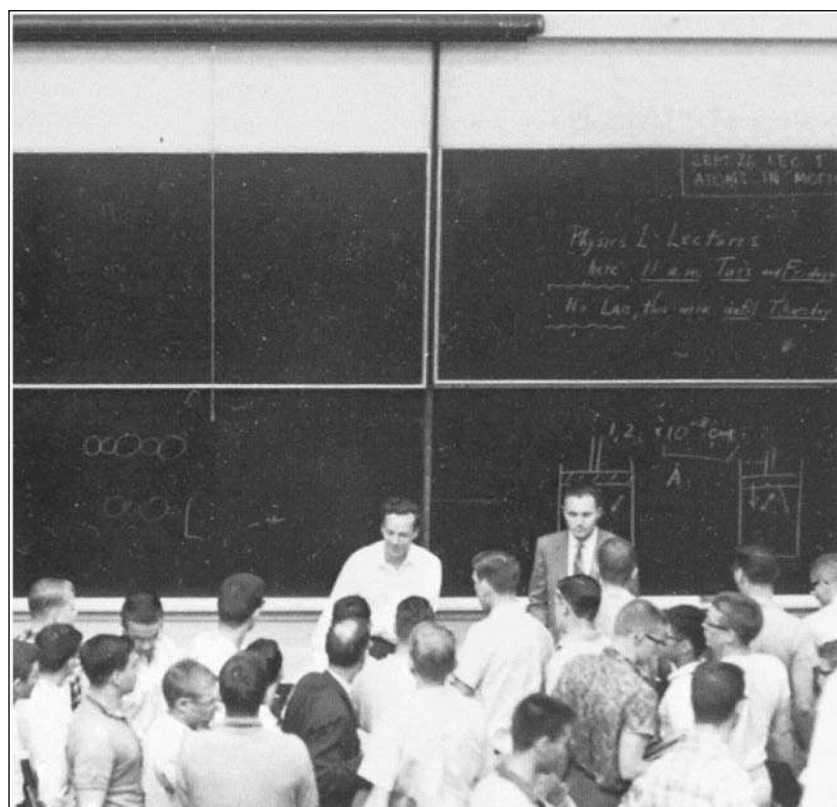
terested way. These people have now, I believe, a first-rate background in physics—and they are, after all, the ones I was trying to get at. But then, “The power of instruction is seldom of much efficacy except in those happy dispositions where it is almost superfluous.” (Gibbon)

Still, I didn’t want to leave any student completely behind, as perhaps I did. I think one way we could help the students more would be by putting more hard work into developing a set of problems which would elucidate some of the ideas in the lectures. Problems give a good opportunity to fill out the material of the lectures and make more realistic, more complete, and more settled in the mind the ideas that have been exposed.

I think, however, that there isn’t any solution to this problem of education other than to realize that the best teaching can be done only when there is a direct individual relationship between a student and a good teacher—a situation in which the student discusses the ideas, thinks about the things, and talks about the things. It’s impossible to learn very much by simply sitting in a lecture, or even by simply doing problems that are assigned. But in our modern times we have so many students to teach that we have to try to find some substitute for the ideal. Perhaps my lectures can make some contribution. Perhaps in some small place where there are individual teachers and students, they may get some inspiration or some ideas from the lectures. Perhaps they will have fun thinking them through—or going on to develop some of the ideas further.


*June 1963*

RICHARD P. FEYNMAN



# ATOMS IN MOTION

## *Introduction*

 This two-year course in physics is presented from the point of view that you, the reader, are going to be a physicist. This is not necessarily the case of course, but that is what every professor in every subject assumes! If you are going to be a physicist, you will have a lot to study: two hundred years of the most rapidly developing field of knowledge that there is. So much knowledge, in fact, that you might think that you cannot learn all of it in four years, and truly you cannot; you will have to go to graduate school too!

Surprisingly enough, in spite of the tremendous amount of work that has been done for all this time it is possible to condense the enormous mass of results to a large extent—that is, to find *laws* which summarize all our knowledge. Even so, the laws are so hard to grasp that it is unfair to you to start exploring this tremendous subject without some kind of map or outline of the relationship of one part of the subject of science to another. Following these preliminary remarks, the first three chapters will therefore outline the relation of physics to the rest of the sciences, the relations of the sciences to each other, and the meaning of science, to help us develop a “feel” for the subject.

You might ask why we cannot teach physics by just giving the basic laws on page one and then showing how they work in all possible circumstances, as we do in Euclidean geometry, where we



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state the axioms and then make all sorts of deductions. (So, not satisfied to learn physics in four years, you want to learn it in four minutes?) We cannot do it in this way for two reasons. First, we do not yet *know* all the basic laws: there is an expanding frontier of ignorance. Second, the correct statement of the laws of physics involves some very unfamiliar ideas which require advanced mathematics for their description. Therefore, one needs a considerable amount of preparatory training even to learn what the *words* mean. No, it is not possible to do it that way. We can only do it piece by piece.

Each piece, or part, of the whole of nature is always merely an *approximation* to the complete truth, or the complete truth so far as we know it. In fact, everything we know is only some kind of approximation, because *we know that we do not know all the laws* as yet. Therefore, things must be learned only to be unlearned again or, more likely, to be corrected.

The principle of science, the definition, almost, is the following: *The test of all knowledge is experiment.* Experiment is the *sole judge* of scientific “truth.” But what is the source of knowledge? Where do the laws that are to be tested come from? Experiment, itself, helps to produce these laws, in the sense that it gives us hints. But also needed is *imagination* to create from these hints the great generalizations—to guess at the wonderful, simple, but very strange patterns beneath them all, and then to experiment to check again whether we have made the right guess. This imagining process is so difficult that there is a division of labor in physics: there are *theoretical* physicists who imagine, deduce, and guess at new laws, but do not experiment; and then there are *experimental* physicists who experiment, imagine, deduce, and guess.

We said that the laws of nature are approximate: that we first find the “wrong” ones, and then we find the “right” ones. Now, how can an experiment be “wrong”? First, in a trivial way: if something is wrong with the apparatus that you did not notice. But these things are easily fixed, and checked back and forth. So without

snatching at such minor things, how *can* the results of an experiment be wrong? Only by being inaccurate. For example, the mass of an object never seems to change: a spinning top has the same weight as a still one. So a “law” was invented: mass is constant, independent of speed. That “law” is now found to be incorrect. Mass is found to increase with velocity, but appreciable increases require velocities near that of light. A *true* law is: if an object moves with a speed of less than one hundred miles a second the mass is constant to within one part in a million. In some such approximate form this is a correct law. So in practice one might think that the new law makes no significant difference. Well, yes and no. For ordinary speeds we can certainly forget it and use the simple constant-mass law as a good approximation. But for high speeds we are wrong, and the higher the speed, the more wrong we are.

Finally, and most interesting, *philosophically we are completely wrong* with the approximate law. Our entire picture of the world has to be altered even though the mass changes only by a little bit. This is a very peculiar thing about the philosophy, or the ideas, behind the laws. Even a very small effect sometimes requires profound changes in our ideas.

Now, what should we teach first? Should we teach the *correct* but unfamiliar law with its strange and difficult conceptual ideas, for example the theory of relativity, four-dimensional space-time, and so on? Or should we first teach the simple “constant-mass” law, which is only approximate, but does not involve such difficult ideas? The first is more exciting, more wonderful, and more fun, but the second is easier to get at first, and is a first step to a real understanding of the first idea. This point arises again and again in teaching physics. At different times we shall have to resolve it in different ways, but at each stage it is worth learning what is now known, how accurate it is, how it fits into everything else, and how it may be changed when we learn more.

Let us now proceed with our outline, or general map, of our understanding of science today (in particular, physics, but also of other

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sciences on the periphery), so that when we later concentrate on some particular point we will have some idea of the background, why that particular point is interesting, and how it fits into the big structure. So, what *is* our overall picture of the world?

*Matter is made of atoms*

If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words? I believe it is the *atomic hypothesis* (or the *atomic fact*, or whatever you wish to call it) that *all things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another*. In that one sentence, you will see, there is an *enormous* amount of information about the world, if just a little imagination and thinking are applied.

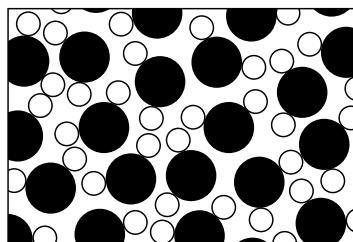
To illustrate the power of the atomic idea, suppose that we have a drop of water a quarter of an inch on the side. If we look at it very closely we see nothing but water—smooth, continuous water. Even if we magnify it with the best optical microscope available—roughly two thousand times—then the water drop will be roughly forty feet across, about as big as a large room, and if we looked rather closely, we would *still* see relatively smooth water—but here and there small football-shaped things swimming back and forth. Very interesting. These are paramecia. You may stop at this point and get so curious about the paramecia with their wiggling cilia and twisting bodies that you go no further, except perhaps to magnify the paramecia still more and see inside. This, of course, is a subject for biology, but for the present we pass on and look still more closely at the water material itself, magnifying it two thousand times again. Now the drop of water extends about fifteen miles across, and if we look very closely at it we see a kind of teeming, something which no longer has a smooth appearance—it looks something like a crowd at a football game as seen from a very great

distance. In order to see what this teeming is about, we will magnify it another two hundred and fifty times and we will see something similar to what is shown in Fig. 1-1. This is a picture of water magnified a billion times, but idealized in several ways. In the first place, the particles are drawn in a simple manner with sharp edges, which is inaccurate. Secondly, for simplicity, they are sketched almost schematically in a two-dimensional arrangement, but of course they are moving around in three dimensions. Notice that there are two kinds of “blobs” or circles to represent the atoms of oxygen (black) and hydrogen (white), and that each oxygen has two hydrogens tied to it. (Each little group of an oxygen with its two hydrogens is called a molecule.) The picture is idealized further in that the real particles in nature are continually jiggling and bouncing, turning and twisting around one another. You will have to imagine this as a dynamic rather than a static picture. Another thing that cannot be illustrated in a drawing is the fact that the particles are “stuck together”—that they attract each other, this one pulled by that one, etc. The whole group is “glued together,” so to speak. On the other hand, the particles do not squeeze through each other. If you try to squeeze two of them too close together, they repel.

The atoms are  $1$  or  $2 \times 10^{-8}$  cm in radius. Now  $10^{-8}$  cm is called an *angstrom* (just as another name), so we say they are  $1$  or  $2$  angstroms ( $\text{\AA}$ ) in radius. Another way to remember their size is this: if an apple is magnified to the size of the earth, then the atoms in the apple are approximately the size of the original apple.

Now imagine this great drop of water with all of these jiggling particles stuck together and tagging along with each other. The water keeps its volume; it does not fall apart, because of the attraction of the molecules for each other. If the drop is on a slope, where it can move from one place to another, the water will flow, but it does not just disappear—things do not just fly apart—because of the molecular attraction. Now the jiggling motion is what we represent as *heat*: when we increase the temperature, we increase the motion. If we heat the water, the jiggling increases and the volume between the atoms increases, and if the heating continues there

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WATER MAGNIFIED ONE BILLION TIMES

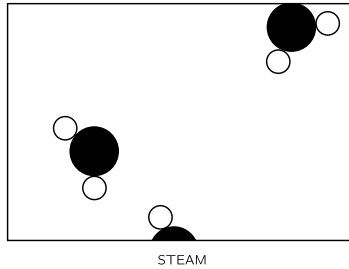
*Figure 1-1*

comes a time when the pull between the molecules is not enough to hold them together and they *do* fly apart and become separated from one another. Of course, this is how we manufacture steam out of water—by increasing the temperature; the particles fly apart because of the increased motion.

In Fig. 1-2 we have a picture of steam. This picture of steam fails in one respect: at ordinary atmospheric pressure there certainly would not be as many as three in this figure. Most squares this size would contain none—but we accidentally have two and a half or three in the picture (just so it would not be completely blank). Now in the case of steam we see the characteristic molecules more clearly than in the case of water. For simplicity, the molecules are drawn so that there is a  $120^\circ$  angle between the hydrogen atoms. In actual fact the angle is  $105^\circ 3'$ , and the distance between the center of a hydrogen and the center of the oxygen is  $0.957 \text{ \AA}$ , so we know this molecule very well.

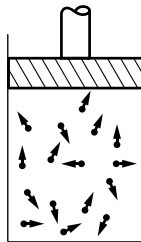
Let us see what some of the properties of steam vapor or any other gas are. The molecules, being separated from one another, will bounce against the walls. Imagine a room with a number of tennis balls (a hundred or so) bouncing around in perpetual motion. When they bombard the wall, this pushes the wall away. (Of course we would have to push the wall back.) This means that the gas exerts a jittery force which our coarse senses (not being ourselves magnified a billion times) feel only as an *average push*. In order to confine a gas we must apply a pressure. Figure 1-3 shows a standard

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*Atoms in Motion**Figure 1-2*

vessel for holding gases (used in all textbooks), a cylinder with a piston in it. Now, it makes no difference what the shapes of water molecules are, so for simplicity we shall draw them as tennis balls or little dots. These things are in perpetual motion in all directions. So many of them are hitting the top piston all the time that to keep it from being patiently knocked out of the tank by this continuous banging, we shall have to hold the piston down by a certain force, which we call the *pressure* (really, the pressure times the area is the force). Clearly, the force is proportional to the area, for if we increase the area but keep the number of molecules per cubic centimeter the same, we increase the number of collisions with the piston in the same proportion as the area was increased.

Now let us put twice as many molecules in this tank, so as to double the density, and let them have the same speed, i.e., the same

*Figure 1-3*

SIX EASY PIECES

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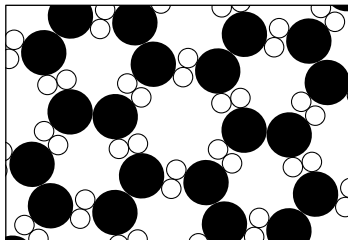
temperature. Then, to a close approximation, the number of collisions will be doubled, and since each will be just as “energetic” as before, the pressure is proportional to the density. If we consider the true nature of the forces between the atoms, we would expect a slight decrease in pressure because of the attraction between the atoms, and a slight increase because of the finite volume they occupy. Nevertheless, to an excellent approximation, if the density is low enough that there are not many atoms, *the pressure is proportional to the density*.

We can also see something else: If we increase the temperature without changing the density of the gas, i.e., if we increase the speed of the atoms, what is going to happen to the pressure? Well, the atoms hit harder because they are moving faster, and in addition they hit more often, so the pressure increases. You see how simple the ideas of atomic theory are.

Let us consider another situation. Suppose that the piston moves inward, so that the atoms are slowly compressed into a smaller space. What happens when an atom hits the moving piston? Evidently it picks up speed from the collision. You can try it by bouncing a ping-pong ball from a forward-moving paddle, for example, and you will find that it comes off with more speed than that with which it struck. (Special example: if an atom happens to be standing still and the piston hits it, it will certainly move.) So the atoms are “hotter” when they come away from the piston than they were before they struck it. Therefore all the atoms which are in the vessel will have picked up speed. This means that *when we compress a gas slowly, the temperature of the gas increases*. So, under slow *compression*, a gas will *increase* in temperature, and under slow *expansion* it will *decrease* in temperature.

We now return to our drop of water and look in another direction. Suppose that we decrease the temperature of our drop of water. Suppose that the jiggling of the molecules of the atoms in the water is steadily decreasing. We know that there are forces of attraction between the atoms, so that after a while they will not be able to jiggle so well. What will happen at very low temperatures is

indicated in Fig. 1-4: the molecules lock into a new pattern which is *ice*. This particular schematic diagram of ice is wrong because it is in two dimensions, but it is right qualitatively. The interesting point is that the material has a *definite place for every atom*, and you can easily appreciate that if somehow or other we were to hold all the atoms at one end of the drop in a certain arrangement, each atom in a certain place, then because of the structure of interconnections, which is rigid, the other end miles away (at our magnified scale) will have a definite location. So if we hold a needle of ice at one end, the other end resists our pushing it aside, unlike the case of water, in which the structure is broken down because of the increased jiggling so that the atoms all move around in different ways. The difference between solids and liquids is, then, that in a solid the atoms are arranged in some kind of an array, called a *crystalline array*, and they do not have a random position at long distances; the position of the atoms on one side of the crystal is determined by that of other atoms millions of atoms away on the other side of the crystal. Figure 1-4 is an invented arrangement for ice, and although it contains many of the correct features of ice, it is not the true arrangement. One of the correct features is that there is a part of the symmetry that is hexagonal. You can see that if we turn the picture around an axis by  $60^\circ$ , the picture returns to itself. So there is a *symmetry* in the ice which accounts for the six-sided appearance of snowflakes. Another thing we can see from Fig. 1-4 is why ice



ICE

*Figure 1-4*



## SIX EASY PIECES

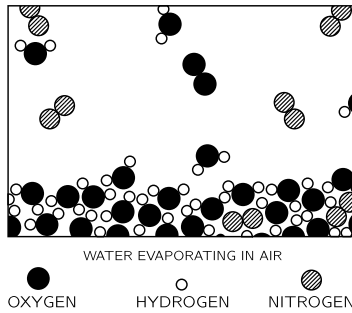
shrinks when it melts. The particular crystal pattern of ice shown here has many “holes” in it, as does the true ice structure. When the organization breaks down, these holes can be occupied by molecules. Most simple substances, with the exception of water and type metal, *expand* upon melting, because the atoms are closely packed in the solid crystal and upon melting need more room to jiggle around, but an open structure collapses, as in the case of water.

Now although ice has a “rigid” crystalline form, its temperature can change—ice has heat. If we wish, we can change the amount of heat. What is the heat in the case of ice? The atoms are not standing still. They are jiggling and vibrating. So even though there is a definite order to the crystal—a definite structure—all of the atoms are vibrating “in place.” As we increase the temperature, they vibrate with greater and greater amplitude, until they shake themselves out of place. We call this *melting*. As we decrease the temperature, the vibration decreases and decreases until, at absolute zero, there is a minimum amount of vibration that the atoms can have, but *not zero*. This minimum amount of motion that atoms can have is not enough to melt a substance, with one exception: helium. Helium merely decreases the atomic motions as much as it can, but even at absolute zero there is still enough motion to keep it from freezing. Helium, even at absolute zero, does not freeze, unless the pressure is made so great as to make the atoms squash together. If we increase the pressure, we *can* make it solidify.

*Atomic processes*

So much for the description of solids, liquids, and gases from the atomic point of view. However, the atomic hypothesis also describes *processes*, and so we shall now look at a number of processes from an atomic standpoint. The first process that we shall look at is associated with the surface of the water. What happens at the surface of the water? We shall now make the picture more complicated—and more realistic—by imagining that the surface is in air. Figure 1-5 shows the surface of water in air. We see the water molecules

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*Atoms in Motion*


*Figure 1-5*

as before, forming a body of liquid water, but now we also see the surface of the water. Above the surface we find a number of things: First of all there are water molecules, as in steam. This is *water vapor*, which is always found above liquid water. (There is an equilibrium between the steam vapor and the water which will be described later.) In addition we find some other molecules—here two oxygen atoms stuck together by themselves, forming an *oxygen molecule*, there two nitrogen atoms also stuck together to make a nitrogen molecule. Air consists almost entirely of nitrogen, oxygen, some water vapor, and lesser amounts of carbon dioxide, argon, and other things. So above the water surface is the air, a gas, containing some water vapor. Now what is happening in this picture? The molecules in the water are always jiggling around. From time to time, one on the surface happens to be hit a little harder than usual, and gets knocked away. It is hard to see that happening in the picture because it is a *still* picture. But we can imagine that one molecule near the surface has just been hit and is flying out, or perhaps another one has been hit and is flying out. Thus, molecule by molecule, the water disappears—it evaporates. But if we *close* the vessel above, after a while we shall find a large number of molecules of water amongst the air molecules. From time to time, one of these vapor molecules comes flying down to the water and gets stuck again. So we see that what looks like a dead, uninteresting thing—a glass of water with a cover, that has been sitting there for perhaps

## SIX EASY PIECES

twenty years—really contains a dynamic and interesting phenomenon which is going on all the time. To our eyes, our crude eyes, nothing is changing, but if we could see it a billion times magnified, we would see that from its own point of view it is always changing: molecules are leaving the surface, molecules are coming back.

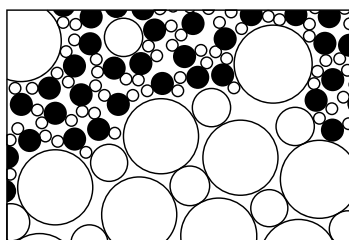
Why do *we* see *no change*? Because just as many molecules are leaving as are coming back! In the long run “nothing happens.” If we then take the top of the vessel off and blow the moist air away, replacing it with dry air, then the number of molecules leaving is just the same as it was before, because this depends on the jiggling of the water, but the number coming back is greatly reduced because there are so many fewer water molecules above the water. Therefore there are more going out than coming in, and the water evaporates. Hence, if you wish to evaporate water turn on the fan!

Here is something else: Which molecules leave? When a molecule leaves it is due to an accidental, extra accumulation of a little bit more than ordinary energy, which it needs if it is to break away from the attractions of its neighbors. Therefore, since those that leave have more energy than the average, the ones that are left have *less* average motion than they had before. So the liquid gradually *cools* if it evaporates. Of course, when a molecule of vapor comes from the air to the water below there is a sudden great attraction as the molecule approaches the surface. This speeds up the incoming molecule and results in generation of heat. So when they leave they take away heat; when they come back they generate heat. Of course when there is no net evaporation the result is nothing—the water is not changing temperature. If we blow on the water so as to maintain a continuous preponderance in the number evaporating, then the water is cooled. Hence, blow on soup to cool it!

Of course you should realize that the processes just described are more complicated than we have indicated. Not only does the water go into the air, but also, from time to time, one of the oxygen or nitrogen molecules will come in and “get lost” in the mass of water molecules, and work its way into the water. Thus the air dissolves in the water; oxygen and nitrogen molecules will work their way

into the water and the water will contain air. If we suddenly take the air away from the vessel, then the air molecules will leave more rapidly than they come in, and in doing so will make bubbles. This is very bad for divers, as you may know.

Now we go on to another process. In Fig. 1-6 we see, from an atomic point of view, a solid dissolving in water. If we put a crystal of salt in the water, what will happen? Salt is a solid, a crystal, an organized arrangement of “salt atoms.” Figure 1-7 is an illustration of the three-dimensional structure of common salt, sodium chloride. Strictly speaking, the crystal is not made of atoms, but of what we call *ions*. An ion is an atom which either has a few extra electrons or has lost a few electrons. In a salt crystal we find chlorine ions (chlorine atoms with an extra electron) and sodium ions (sodium atoms with one electron missing). The ions all stick together by electrical attraction in the solid salt, but when we put them in the water we find, because of the attractions of the negative oxygen and positive hydrogen for the ions, that some of the ions jiggle loose. In Fig. 1-6 we see a chlorine ion getting loose, and other atoms floating in the water in the form of ions. This picture was made with some care. Notice, for example, that the hydrogen ends of the water molecules are more likely to be near the chlorine ion, while near the sodium ion we are more likely to find the oxygen end, because the



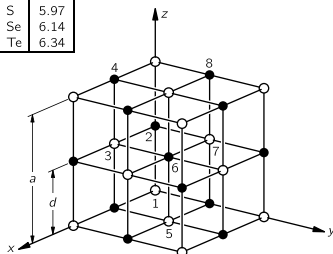
SALT DISSOLVING IN WATER



*Figure 1-6*

## SIX EASY PIECES

Crystal	●	○	$a$ (Å)
Rocksalt	Na	Cl	5.64
	K	Cl	6.28
	Ag	Cl	5.54
Sylvine	Mg	O	4.20
	Pb	S	5.97
	Pb	Se	6.14
	Pb	Te	6.34



Nearest neighbor  
distance  $d = a/2$

Figure 1-7

sodium is positive and the oxygen end of the water is negative, and they attract electrically. Can we tell from this picture whether the salt is *dissolving in* water or *crystallizing out* of water? Of course we *cannot* tell, because while some of the atoms are leaving the crystal other atoms are rejoining it. The process is a *dynamic* one, just as in the case of evaporation, and it depends on whether there is more or less salt in the water than the amount needed for equilibrium. By equilibrium we mean that situation in which the rate at which atoms are leaving just matches the rate at which they are coming back. If there is almost no salt in the water, more atoms leave than return, and the salt dissolves. If, on the other hand, there are too many “salt atoms,” more return than leave, and the salt is crystallizing.

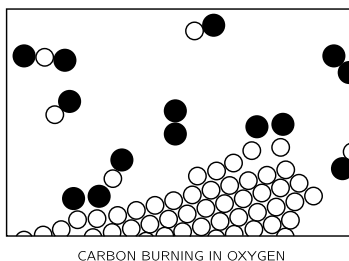
In passing, we mention that the concept of a *molecule* of a substance is only approximate and exists only for a certain class of substances. It is clear in the case of water that the three atoms are actually stuck together. It is not so clear in the case of sodium chloride in the solid. There is just an arrangement of sodium and chlorine ions in a cubic pattern. There is no natural way to group them as “molecules of salt.”

Returning to our discussion of solution and precipitation, if we increase the temperature of the salt solution, then the rate at which

atoms are taken away is increased, and so is the rate at which atoms are brought back. It turns out to be very difficult, in general, to predict which way it is going to go, whether more or less of the solid will dissolve. Most substances dissolve more, but some substances dissolve less, as the temperature increases.

### *Chemical reactions*

In all of the processes which have been described so far, the atoms and the ions have not changed partners, but of course there are circumstances in which the atoms do change combinations, forming new molecules. This is illustrated in Fig. 1-8. A process in which the rearrangement of the atomic partners occurs is what we call a *chemical reaction*. The other processes so far described are called physical processes, but there is no sharp distinction between the two. (Nature does not care what we call it, she just keeps on doing it.) This figure is supposed to represent carbon burning in oxygen. In the case of oxygen, *two* oxygen atoms stick together very strongly. (Why do not *three* or even *four* stick together? That is one of the very peculiar characteristics of such atomic processes. Atoms are very special: they like certain particular partners, certain particular directions, and so on. It is the job of physics to analyze why each one wants what it wants. At any rate, two oxygen atoms form, saturated and happy, a molecule.)



*Figure 1-8*

## SIX EASY PIECES

The carbon atoms are supposed to be in a solid crystal (which could be graphite or diamond\*). Now, for example, one of the oxygen molecules can come over to the carbon, and each atom can pick up a carbon atom and go flying off in a new combination—"carbon-oxygen"—which is a molecule of the gas called carbon monoxide. It is given the chemical name CO. It is very simple: the letters "CO" are practically a picture of that molecule. But carbon attracts oxygen much more than oxygen attracts oxygen or carbon attracts carbon. Therefore in this process the oxygen may arrive with only a little energy, but the oxygen and carbon will snap together with a tremendous vengeance and commotion, and everything near them will pick up the energy. A large amount of motion energy, kinetic energy, is thus generated. This of course is *burning*; we are getting *heat* from the combination of oxygen and carbon. The heat is ordinarily in the form of the molecular motion of the hot gas, but in certain circumstances it can be so enormous that it generates *light*. That is how one gets *flames*.

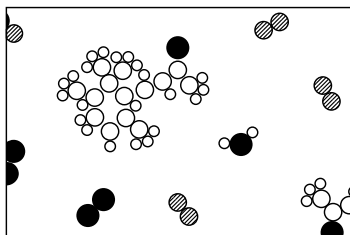
In addition, the carbon monoxide is not quite satisfied. It is possible for it to attach another oxygen, so that we might have a much more complicated reaction in which the oxygen is combining with the carbon, while at the same time there happens to be a collision with a carbon monoxide molecule. One oxygen atom could attach itself to the CO and ultimately form a molecule, composed of one carbon and two oxygens, which is designated CO<sub>2</sub> and called carbon dioxide. If we burn the carbon with very little oxygen in a very rapid reaction (for example, in an automobile engine, where the explosion is so fast that there is not time for it to make carbon dioxide) a considerable amount of carbon monoxide is formed. In many such rearrangements, a very large amount of energy is released, forming explosions, flames, etc., depending on the reactions. Chemists have studied these arrangements of the atoms, and found that every substance is some type of *arrangement of atoms*.

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\* One *can* burn a diamond in air.

To illustrate this idea, let us consider another example. If we go into a field of small violets, we know what “that smell” is. It is some kind of *molecule*, or arrangement of atoms, that has worked its way into our noses. First of all, *how* did it work its way in? That is rather easy. If the smell is some kind of molecule in the air, jiggling around and being knocked every which way, it might have *accidentally* worked its way into the nose. Certainly it has no particular desire to get into our nose. It is merely one helpless part of a jostling crowd of molecules, and in its aimless wanderings this particular chunk of matter happens to find itself in the nose.

Now chemists can take special molecules like the odor of violets, and analyze them and tell us the *exact arrangement* of the atoms in space. We know that the carbon dioxide molecule is straight and symmetrical:  $\text{O}=\text{C}=\text{O}$ . (That can be determined easily, too, by physical methods.) However, even for the vastly more complicated arrangements of atoms that there are in chemistry, one can, by a long, remarkable process of detective work, find the arrangements of the atoms. Figure 1-9 is a picture of the air in the neighborhood of a violet; again we find nitrogen and oxygen in the air, and water vapor. (Why is there water vapor? Because the violet is *wet*. All plants transpire.) However, we also see a “monster” composed of carbon atoms, hydrogen atoms, and oxygen atoms, which have picked a certain particular pattern in which to be arranged. It is a much more complicated arrangement than that of carbon dioxide;



ODOR OF VIOLETS

*Figure 1-9*



## SIX EASY PIECES

in fact, it is an enormously complicated arrangement. Unfortunately, we cannot picture all that is really known about it chemically, because the precise arrangement of all the atoms is actually known in three dimensions, while our picture is in only two dimensions. The six carbons which form a ring do not form a flat ring, but a kind of “puckered” ring. All of the angles and distances are known. So a chemical *formula* is merely a picture of such a molecule. When the chemist writes such a thing on the blackboard, he is trying to “draw,” roughly speaking, in two dimensions. For example, we see a “ring” of six carbons, and a “chain” of carbons hanging on the end, with an oxygen second from the end, three hydrogens tied to that carbon, two carbons and three hydrogens sticking up here, etc.

How does the chemist find what the arrangement is? He mixes bottles full of stuff together, and if it turns red, it tells him that it consists of one hydrogen and two carbons tied on here; if it turns blue, on the other hand, that is not the way it is at all. This is one of the most fantastic pieces of detective work that has ever been done—organic chemistry. To discover the arrangement of the atoms in these enormously complicated arrays the chemist looks at what happens when he mixes two different substances together. The physicist could never quite believe that the chemist knew what he was talking about when he described the arrangement of the atoms. For about twenty years it has been possible, in some cases, to look at such molecules (not quite as complicated as this one, but some which contain parts of it) by a physical method, and it has been possible to locate every atom, not by looking at colors, but by *measuring where they are*. And lo and behold!, the chemists are almost always correct.

It turns out, in fact, that in the odor of violets there are three slightly different molecules, which differ only in the arrangement of the hydrogen atoms.

One problem of chemistry is to name a substance, so that we will know what it is. Find a name for this shape! Not only must the name

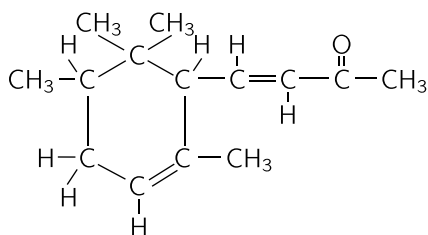


Figure 1-10 The substance pictured is  $\alpha$ -irone.

tell the shape, but it must also tell that here is an oxygen atom, there a hydrogen—exactly what and where each atom is. So we can appreciate that the chemical names must be complex in order to be complete. You see that the name of this thing in the more complete form that will tell you the structure of it is 4-(2, 2, 3, 6 tetramethyl-5-cyclohexenyl)-3-buten-2-one, and that tells you that this is the arrangement. We can appreciate the difficulties that the chemists have, and also appreciate the reason for such long names. It is not that they wish to be obscure, but they have an extremely difficult problem in trying to describe the molecules in words!

How do we *know* that there are atoms? By one of the tricks mentioned earlier: we make the *hypothesis* that there are atoms, and one after the other results come out the way we predict, as they ought to if things *are* made of atoms. There is also somewhat more direct evidence, a good example of which is the following: The atoms are so small that you cannot see them with a light microscope—in fact, not even with an *electron* microscope. (With a light microscope you can only see things which are much bigger.) Now if the atoms are always in motion, say in water, and we put a big ball of something in the water, a ball much bigger than the atoms, the ball will jiggle around—much as in a push ball game, where a great big ball is pushed around by a lot of people. The people are pushing in various directions, and the ball moves around the field in an irregular fashion. So, in the same way, the “large ball” will move because of