STANFORD LINEAR ACCELERATOR CENTER

Beam Line

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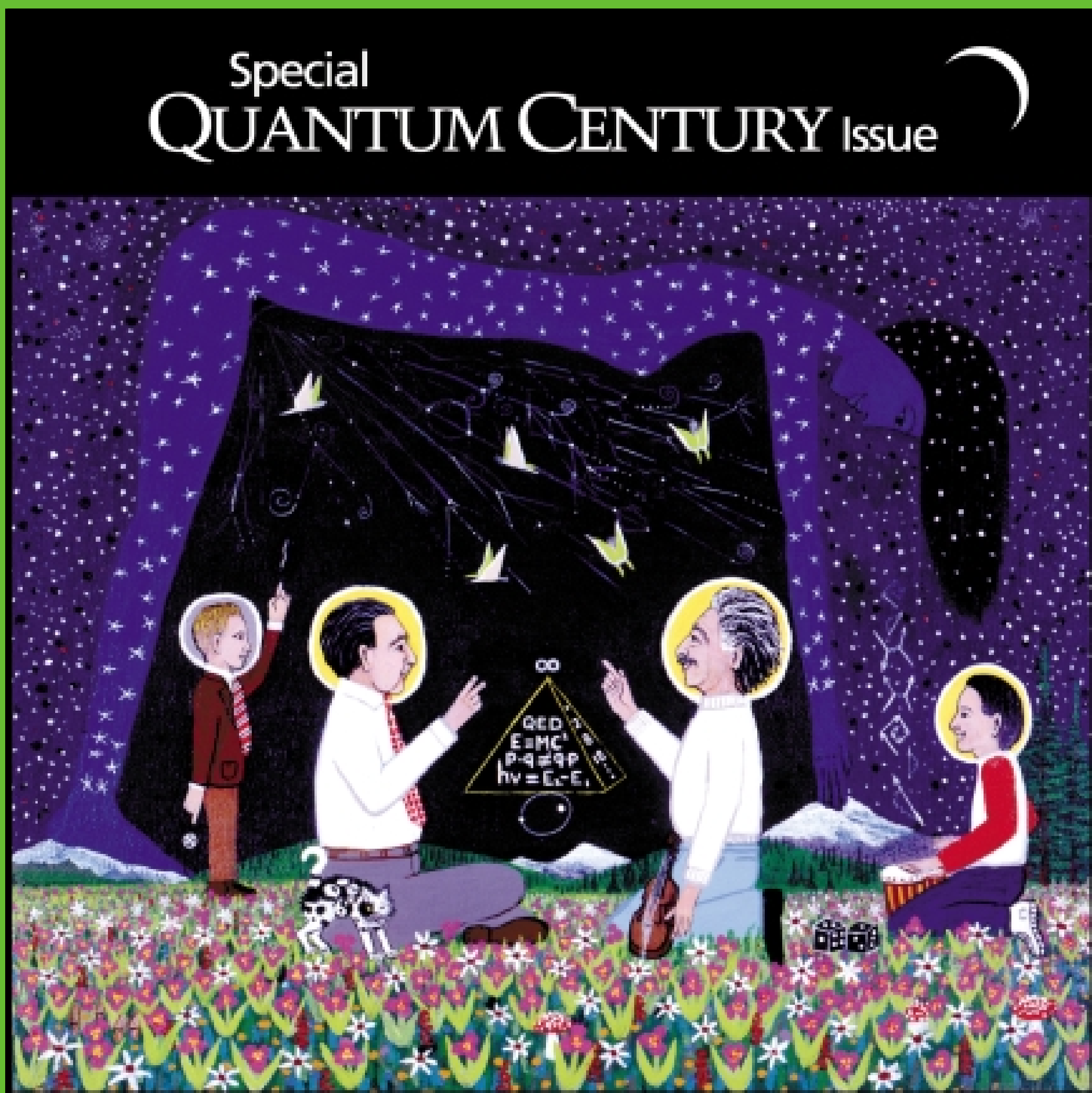

Beam Line

A PERIODICAL OF PARTICLE PHYSICS

SUMMER/FALL 2000 VOL. 30, NUMBER 2

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Cover: "Einstein and the Quantum Mechanics," by artist David Martinez © 1994. The original is acrylic on canvas, 16"×20". Martinez's notes about the scene are reproduced in the adjoining column, and you can read more about his philosophy in the "Contributors" section on page 60. His website is http://members.aol.com/elchato/index.html and from there you can view more of his paintings. The Beam Line *is extremely grateful to him and to his wife Terry for allowing us to reproduce this imaginative and fun image.*

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Einstein and The Quantum Mechanics

Werner Heisenberg illustrates his Uncertainty Principle by pointing down with his right hand to indicate the location of an electron and pointing up with his other hand to its wave to indicate its momentum. At any instant, the more certain we are about the momentum of a quantum, the less sure we are of its exact location.

Niels Bohr gestures upward with two fingers to emphasize the dual, complementary nature of reality. A quantum is simultaneously a wave and a particle, but any experiment can only measure one aspect or the other. Bohr argued that theories about the Universe must include a factor to account for the effects of the observer on any measurement of quanta. Bohr and Heisenberg argued that exact predictions in quantum mechanics are limited to statistical descriptions of group behavior. This made Einstein declare that he could not believe that God plays dice with the Universe.

Albert Einstein holds up one finger to indicate his belief that the Universe can be described with one unified field equation. Einstein discovered both the relativity of time and the mathematical relationship between energy and matter. He devoted the rest of his life to formulating a unified field theory. Even though we must now use probabilities to describe quantum events, Einstein expressed the hope that future scientists will find a hidden order behind quantum mechanics.

Richard Feynman plays the bongo drums, with Feynman diagrams of virtual particles rising up like music notes. One of his many tricks was simplifying the calculation of quantum equations by eliminating the infinities that had prevented real solutions. Feynman invented quantum electrodynamics, the most practical system for solving quantum problems.

Schrödinger's cat is winking and rubbing up to Bohr. The blue woman arching over the Earth is Nut, the Sky Goddess of Egypt. She has just thrown the dice behind Einstein's back. Nut is giving birth to showers of elementary particles which cascade over the butterflies of chaos.

—David Martinez

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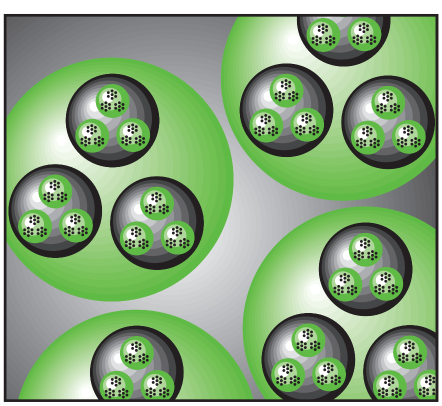
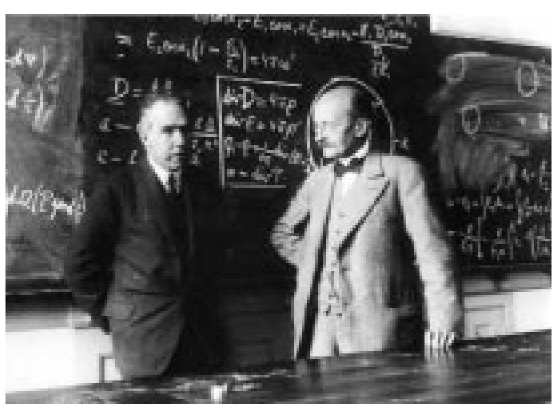




FOREWORD

The Future of the Quantum T

by JAMES BJORKEN

Max Planck, circa 1910
(Courtesy AIP Emilio Segrè Visual Archives)

IN THIS ISSUE of the *Beam Line*, we celebrate the one hundredth anniversary of the birth of the quantum theory. The story of how Max Planck started it all is one of the most marvelous in all of science. It is a favorite of mine, so much so that I have already written about it (see "Particle Physics—Where Do We Go From Here?" in the Winter 1992 *Beam Line*, Vol. 22, No. 4). Here I will only quote again what the late Abraham Pais said about Planck: "His reasoning was mad, but his madness had that divine quality that only the greatest transitional figures can bring to science."*

A century later, the madness has not yet completely disappeared. Science in general has a way of producing results which defy human intuition. But it is fair to say that the winner in this category is the quantum theory. In my mind quantum paradoxes such as the Heisenberg uncertainty principle, Schrödinger's cat, "collapse of the wave packet," and so forth are far more perplexing and challenging than those of relativity, whether they be the twin paradoxes of special relativity or the black hole physics of classical general relativity. It is often said that no one *really* understands quantum theory, and I would be the last to disagree.

In the contributions to this issue, the knotty questions of the interpretation of quantum theory are, mercifully, not addressed. There will be no mention of the debates between Einstein and Bohr, nor the later attempts by

**Abraham Pais,* Subtle is the Lord: Science and the Life of Albert Einstein, *Oxford U. Press, 1982.*

heory

Paul Ehrenfest

Albert Einstein and Neils Bohr in the late 1920s. (Courtesy AIP Emilio Segrè Visual Archives)

Bohm, Everett, and others to find interpretations of the theory different from the original "Copenhagen interpretation" of Bohr and his associates. Instead, what is rightfully emphasized is the overwhelming practical success of these revolutionary ideas. Quantum theory works. It never fails. And the scope of the applications is enormous. As Leon Lederman, Nobel Laureate and Director Emeritus of Fermilab, likes to point out, more than 25 percent of the gross national product is dependent upon technology that springs in an essential way from quantum phenomena.*

Nevertheless, it is hard not to sympathize with Einstein and feel that there is something incomplete about the present status of quantum theory. Perhaps the equations defining the theory are not exactly correct, and corrections will eventually be defined and their effects observed. This is not a popular point of view. But there does exist a minority school of thought which asserts that only for sufficiently small systems is the quantum theory accurate, and that for large complex quantum systems, hard to follow in exquisite detail, there

*Leon Lederman, The God Particle (If the Universe is the Answer, What is the Question?), Houghton Mifflin, 1993.

may be a small amount of some kind of extra intrinsic “noise” term or nonlinearity in the fundamental equations, which effectively eliminates paradoxes such as the “collapse of the wave packet.”

Down through history most of the debates on the foundations of quantum theory produced many words and very little action, and remained closer to the philosophy of science than to real experimental science. John Bell brought some freshness to the subject. The famous theorem that bears his name initiated an experimental program to test some of the fundamentals. Nevertheless, it would have been an enormous shock, at least to me, if any discrepancy in such experiments had been found, because the searches involved simple atomic systems, not so different from elementary particle systems within which very subtle quantum effects have for some time been clearly demonstrated. A worthy challenge to the quantum theory in my opinion must go much further and deeper.

What might such a challenge be? At present, one clear possibility which is actively pursued is in the realm of string theory, which attempts an extension of Einstein gravity into the domain of very short distances, where quantum effects dominate. In the present incarnations, it is the theory of gravity that yields ground and undergoes modifications and generalizations, with the quantum theory left essentially intact. But it seems to me that the alternative must also be entertained—that the quantum theory itself does not survive the synthesis. This, however, is easier said than done. And the problem with each option is that the answer needs to be found with precious little assistance from experiment. This is in stark contrast with the development of quantum theory itself, which was driven from initiation to completion by a huge number of experiments, essentially guiding the theorists to the final equations.

Another approach has been recently laid out by Frank Wilczek in a very interesting essay in *Physics Today*.* He compares the development of the equations of quantum theory with those of Maxwell's electrodynamics. Both were first laboriously put together from experimental evidence. In both cases the interpretations of what the equations meant came later. In the case of electrodynamics, the ultimate verdict on Maxwell's equations is that at a deep level they express statements about symmetry. (In physics jargon, Maxwell's equations express the fact that electrodynamics is gauge invariant and Lorentz covariant.) Wilczek notes that there is no similar deep basis for the equations of quantum mechanics, and he looks forward to statements of symmetry as the future expression of the true meaning of the quantum theory. But if there are such symmetries, they are not now known or at least not yet recognized. Wilczek does cite a pioneering suggestion of Hermann Weyl, which might provide at least a clue as to what might be done. But even if Wilczek is on the right track, there is again the problem that theorists will be largely on their own, with very little help to be expected from experiment.

There is, however, a data-driven approach on the horizon. It is a consequence of the information revolution. In principle, quantum systems may be used to create much more powerful computers than now exist. So there is a strong push to develop the concepts and the technology to create large-scale quantum computers. If this happens, the foundations of quantum mechanics will be tested on larger and larger, more complex physical systems. And if quantum mechanics in the large needs to be modified, these computers may not work as they are supposed to. If this happens, it will be just one more example of how a revolution in technology can lead to a revolution in fundamental science.

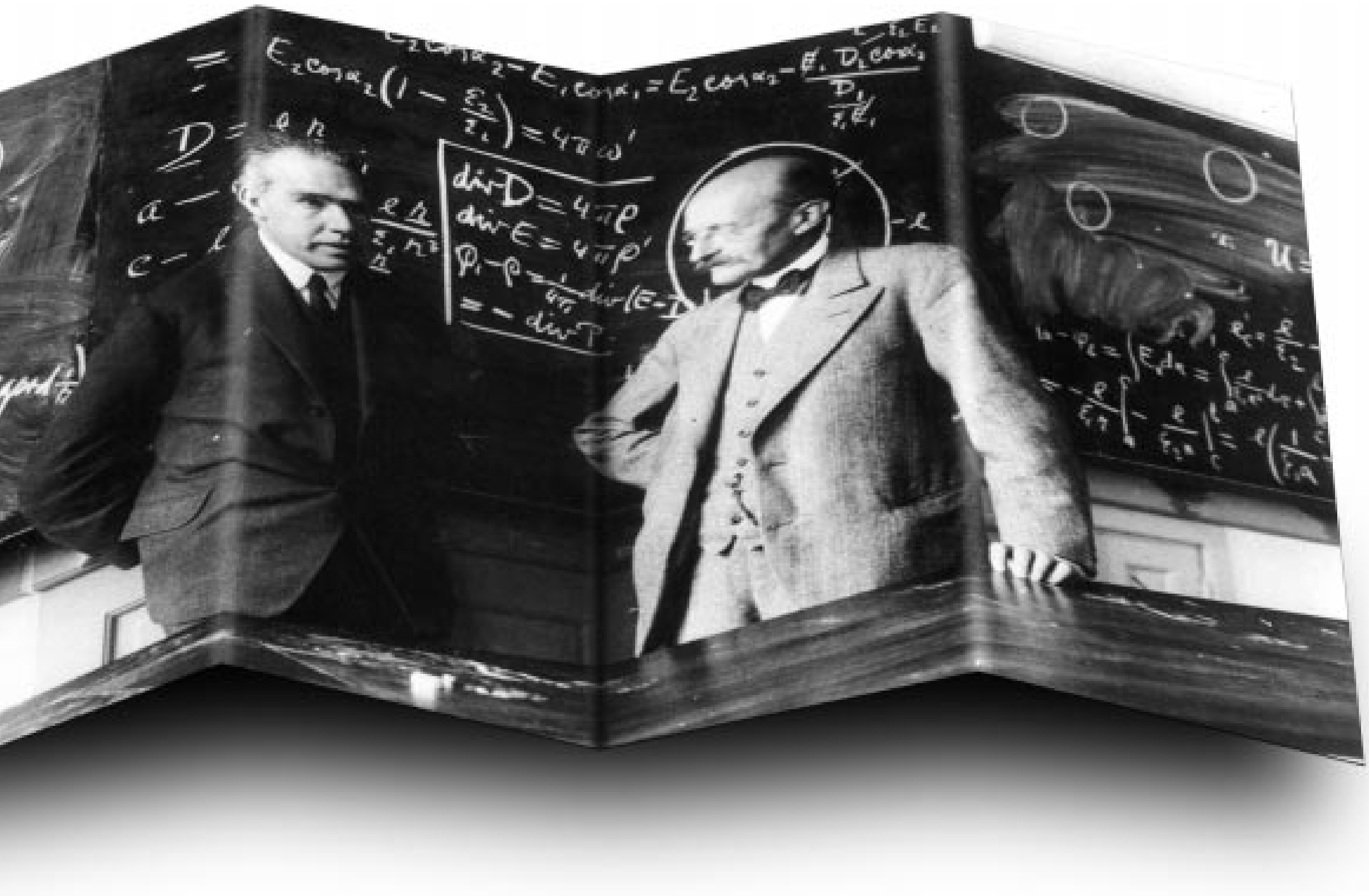
**Frank Wilczek,* Physics Today, *June 2000, Vol. 53, No. 6, p. 11.*

THE ORIGINS OF THE QUANTUM THEORY

by CATHRYN CARSON

WHAT IS A QUANTUM THEORY? We have been asking that question for a long time, ever since Max Planck introduced the element of discontinuity we call the quantum a century ago. Since then, the chunkiness of Nature (or at least of our theories about it) has been built into our basic conception of the world. It has prompted a fundamental rethinking of physical theory. At the same time it has helped make sense of a whole range of peculiar behaviors manifested principally at microscopic levels.

From its beginning, the new regime was symbolized by Planck's constant *h*, introduced in his famous paper of 1900. Measuring the world's departure from smooth, continuous behavior, *h* proved to be a very small number, but different from zero. Wherever it appeared, strange phenomena came with it. What it really meant was of course mysterious. While the quantum era was inaugurated in 1900, a quantum theory would take much longer to jell. Introducing discontinuity was a tentative step, and only a first one. And even thereafter, the recasting of physical theory was hesitant and slow. Physicists pondered for years what a quantum theory might be. Wondering how to integrate it with the powerful apparatus of nineteenth-century physics, they also asked what relation it bore to existing, "classical" theories. For some the answers crystallized with quantum mechanics, the result of a quarter-century's labor. Others held out for further rethinking. If the outcome was not to the satisfaction of all, still the quantum theory proved remarkably

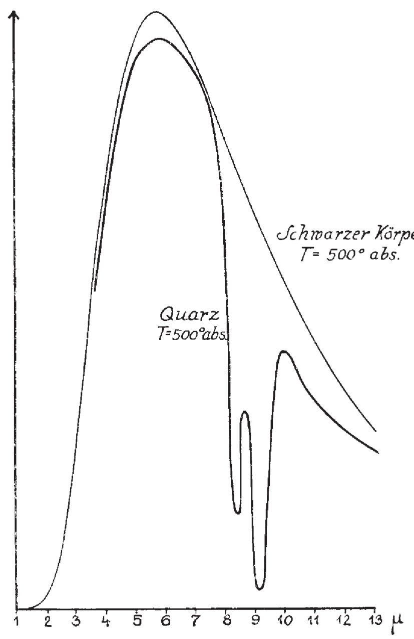


successful, and the puzzlement along the way, despite its frustrations, can only be called extraordinarily productive.

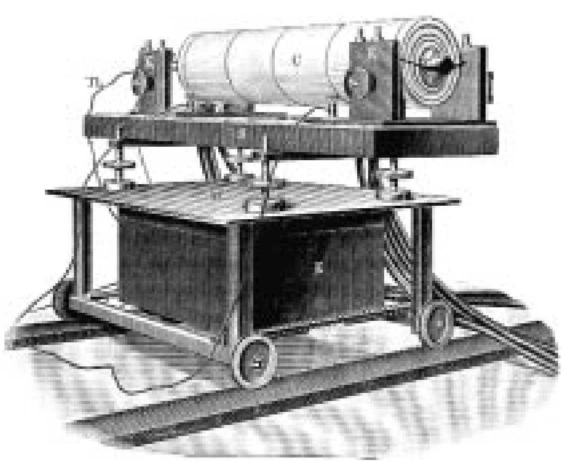
INTRODUCING *h*

Two theorists, Niels Bohr and Max Planck, at the blackboard. (Courtesy Emilio Segrè Visual Archives, Margrethe Bohr Collection)

The story began inconspicuously enough on December 14, 1900. Max Planck was giving a talk to the German Physical Society on the continuous spectrum of the frequencies of light emitted by an ideal heated body. Some two months earlier this 42-year-old theorist had presented a formula capturing some new experimental results. Now, with leisure to think and more time at his disposal, he sought to provide a physical justification for his formula. Planck pictured a piece of matter, idealizing it somewhat, as equivalent to a collection of oscillating electric charges. He then imagined distributing its energy in discrete chunks proportional to the frequencies of oscillation. The constant of proportionality he chose to call h; we would now write $\varepsilon = hf$. The frequencies of oscillation determined the frequencies of the emitted light. A twisted chain of reasoning then reproduced Planck's postulated formula, which now involved the same natural constant h.



An ideal blackbody spectrum (Schwarzer Körper) and its real-world approximation (quartz). (From Clemens Schaefer, Einführung in die Theoretische Physik, 1932).



Experimental setup for measuring blackbody radiation. (The blackbody is the tube labeled C.) This design was a product of Germany's Imperial Institute of Physics and Technology in Berlin, where studies of blackbodies were pursued with an eye toward industrial standards of luminous intensity. (From Müller-Pouillets Lehrbuch der Physik, 1929).

Looking back on the event, we might expect revolutionary fanfare. But as so often in history, matters were more ambiguous. Planck did not call his energy elements quanta and was not inclined to stress their discreteness, which made little sense in any familiar terms. So the meaning of his procedure only gradually became apparent. Although the problem he was treating was pivotal in its day, its implications were at first thought to be confined.

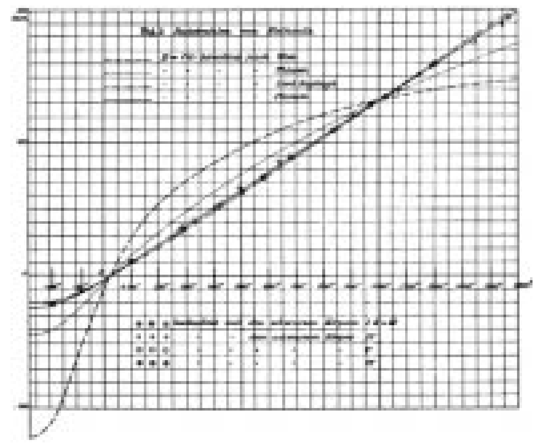
BLACKBODIES

The behavior of light in its interaction with matter was indeed a key problem of nineteenth-century physics. Planck was interested in the two theories that overlapped in this domain. The first was electrodynamics, the theory of electricity, magnetism, and light waves, brought to final form by James Clerk Maxwell in the 1870s. The second, dating from roughly the same period, was thermodynamics and statistical mechanics, governing transformations of energy and its behavior in time. A pressing question was whether these two grand theories could be fused into one, since they started from different fundamental notions.

Beginning in the mid-1890s, Planck took up a seemingly narrow problem, the interaction of an oscillating charge with its electromagnetic field. These studies, however, brought him into contact with a long tradition of work on the emission of light. Decades earlier it had been recognized that perfectly absorbing ("black") bodies provided a standard for emission as well. Then over the years a small industry had grown up around the study of such objects (and their real-world substitutes, like soot). A small group of theorists occupied themselves with the thermodynamics of radiation, while a host of experimenters labored over heated bodies to fix temperature, determine intensity, and characterize deviations from blackbody ideality (see the graph above). After scientists pushed the practical realization of an old idea—that a closed tube with a small hole constituted a near-ideal blackbody—this "cavity radiation" allowed ever more reliable measurements. (See illustration at left.)

Now Planck's oscillating charges emitted and absorbed radiation, so they could be used to model a blackbody. Thus everything seemed to fall into place in 1899 when he reproduced a formula that a colleague had derived by less secure means. That was convenient; everyone agreed that Willy Wien's formula matched the observations. The trouble was that immediately afterwards, experimenters began finding deviations. At low frequencies, Wien's expression became increasingly untenable, while elsewhere it continued to work well enough. Informed of the results in the fall of 1900, on short notice Planck came up with a reasonable interpolation. With its adjustable constants his formula seemed to fit the experiments (see graph at right). Now the question became: Where might it come from? What was its physical meaning?

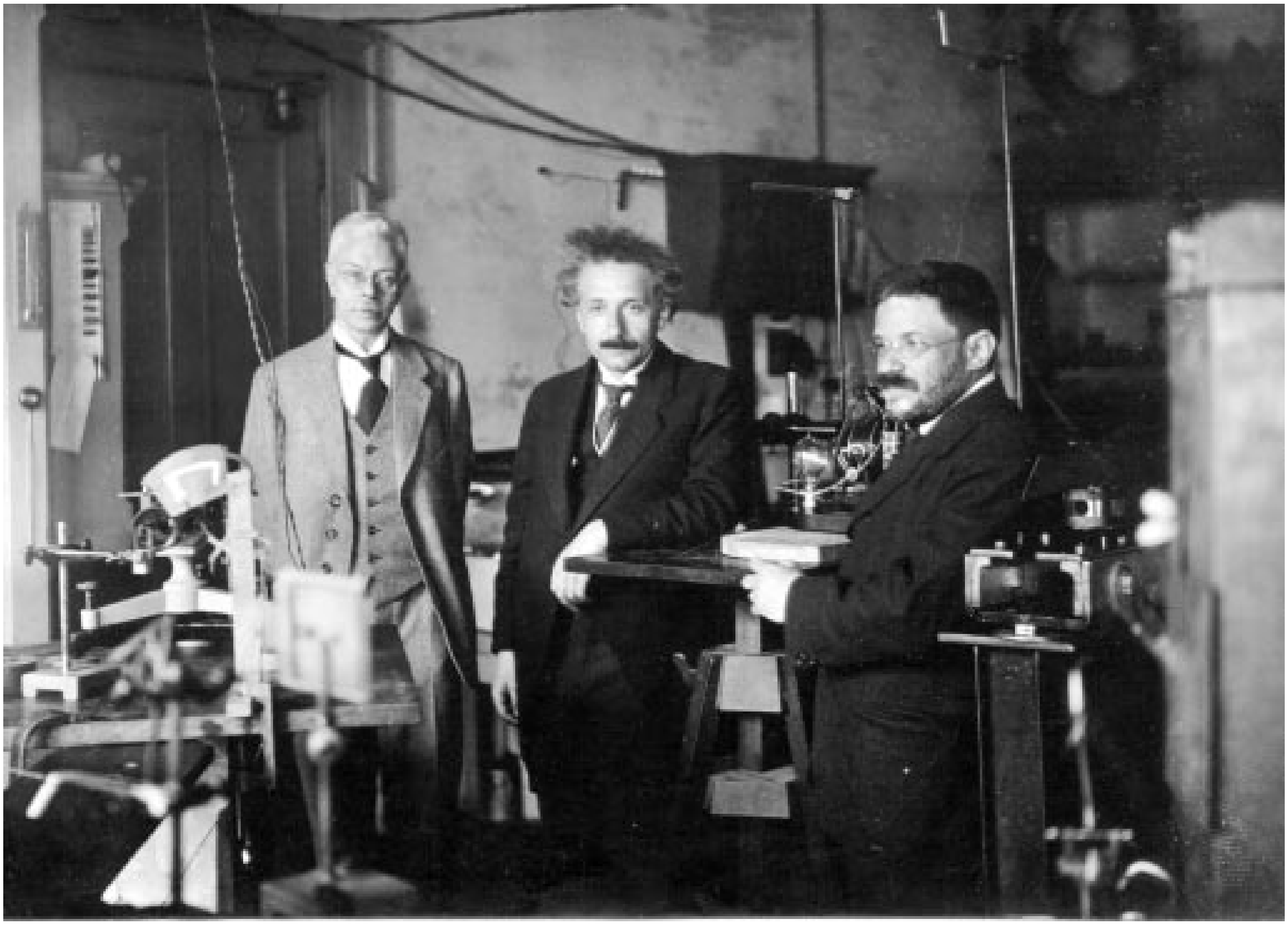
As we saw, Planck managed to produce a derivation. To get the right statistical results, however, he had to act as though the energy involved were divided up into elements $\varepsilon = hf$. The derivation was a success and splendidly reproduced the experimental data. Its meaning was less clear. After all, Maxwell's theory already gave a beautiful account of light—and treated it as a wave traveling in a continuous medium. Planck did not take the constant h to indicate a physical discontinuity, a real atomicity of energy in a substantive sense. None of his colleagues made much of this possibility, either, until Albert Einstein took it up five years later.



Experimental and theoretical results on the blackbody spectrum. The data points are experimental values; Planck's formula is the solid line. (Reprinted from H. Rubens and F. Kurlbaum, Annalen der Physik, *1901.)*

MAKING LIGHT QUANTA REAL

Of Einstein's three great papers of 1905, the one "On a Heuristic Point of View Concerning the Production and Transformation of Light" was the piece that the 26-year-old patent clerk labeled revolutionary. It was peculiar, he noted, that the electromagnetic theory of light assumed a continuum, while current accounts of matter started from discrete atoms. Could discontinuity be productive for light as well? However indispensable Maxwell's equations might seem, for some interesting phenomena they proved inadequate. A key example was blackbody radiation, which Einstein now looked at in a way different from Planck. Here a rigorously classical treatment, he showed,



Pieter Zeeman, Albert Einstein, and Paul Ehrenfest (left to right) in Zeeman's Amsterdam laboratory. (Courtesy Emilio Segrè Visual Archives, W. F. Meggers Collection)

yielded a result not only wrong but also absurd. Even where Wien's law was approximately right (and Planck's modification unnecessary), elementary thermodynamics forced light to behave as though it were localized in discrete chunks. Radiation had to be parcelled into what Einstein called "energy quanta." Today we would write $E = hf$.

Discontinuity was thus endemic to the electromagnetic world. Interestingly, Einstein did not refer to Planck's constant h, believing his approach to be different in spirit. Where Planck had looked at oscillating charges, Einstein applied thermodynamics to the light itself. It was only later that Einstein went back and showed how Planck's work implied real quanta. In the meantime, he offered a further, radical extension. If light behaves on its own as though composed of such quanta, then perhaps it is also emitted and absorbed in that fashion. A few easy considerations then yielded a law for the photoelectric effect, in which light ejects electrons from the surface of a metal. Einstein provided not only a testable hypothesis but also a new way of measuring the constant h (see table on the next page).

Today the photoelectric effect can be checked in a college laboratory. In 1905, however, it was far from trivial. So it would remain for more than a decade. Even after Robert Millikan confirmed Einstein's prediction, he and others balked at the underlying quantum hypothesis. It still violated everything known about light's wavelike behavior (notably, interference) and hardly seemed reconcilable with Maxwell's equations. When Einstein was awarded the Nobel Prize, he owed the honor largely to the photoelectric effect. But the citation specifically noted his discovery of the law, not the explanation that he proposed.

The relation of the quantum to the wave theory of light would remain a point of puzzlement. Over the next years Einstein would only sharpen the contradiction. As he showed, thermodynamics ineluctably required both classical waves and quantization. The two aspects were coupled: both were necessary, and at the same time. In the process, Einstein moved even closer to attributing to light a whole panoply of particulate properties. The particle-like quantum, later named the photon, would prove suggestive for explaining things like the scattering of X rays. For that 1923 discovery, Arthur Compton would win the Nobel Prize. But there we get ahead of the story. Before notions of wave-particle duality could be taken seriously, discontinuity had to demonstrate its worth elsewhere.

BIRGE'S CALCULATION OF PLANCK'S UNIVERSAL CONSTANT h BY VARIOUS METHODS

Value of h.	Method.	Remarks.
$6{\cdot}551 \pm 0{\cdot}009$	$\sigma = 5{\cdot}72$	Total radiation
$6{\cdot}557 \pm 0{\cdot}013$	$C_2 = 14330$	Spectral radiation
$6{\cdot}542 \pm 0{\cdot}011$	Rydberg constant	Bohr's theory of atomic structure
$6{\cdot}578 \pm 0{\cdot}026$	Photo-electric equations	Einstein's equation
$6{\cdot}555 \pm 0{\cdot}009$	X-rays	Quantum relation
$6{\cdot}560 \pm 0{\cdot}014$	Ultimate rational units	Theory of Lewis and Adams
$6{\cdot}579 \pm 0{\cdot}021$	Ionisation potential	..

Mean value, $h = (6{\cdot}5543 \pm 0{\cdot}0025)10^{-27}$ erg sec.

(From W. W. Coblentz, Radiation, Determination of the Constants and Verification of the Laws in A Dictionary of Applied Physics, Vol. 4, Ed. Sir Richard Glazebrook, 1923)

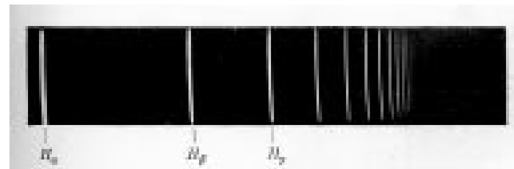
BEYOND LIGHT

As it turned out, the earliest welcome given to the new quantum concepts came in fields far removed from the troubled theories of radiation. The first of these domains, though hardly the most obvious, was the theory of specific heats. The specific heat of a substance determines how much of its energy changes when its temperature is raised. At low temperatures, solids display peculiar behavior. Here Einstein suspected—again we meet Einstein—that the deviance might be explicable on quantum grounds. So he reformulated Planck's problem to handle a lattice of independently vibrating atoms. From this highly simplistic model, he obtained quite reasonable predictions that involved the same quantity hf, now translated into the solid-state context.

There things stood for another three years. It took the sudden attention of the physical chemist Walther Nernst to bring quantum theories of specific heats to general significance. Feeling his way towards a new law of thermodynamics, Nernst not only bolstered Einstein's ideas with experimental results, but also put them on the agenda for widespread discussion. It was no accident, and to a large degree Nernst's doing, that the first Solvay Congress in 1911 dealt precisely with radiation theory and quanta (see photograph below). Einstein spoke on specific heats, offering additional comments on electromagnetic radiation. If the quantum was born in 1900, the Solvay meeting was, so to speak, its social debut.

What only just began to show up in the Solvay colloquy was the other main realm in which discontinuity would prove its value. The technique of quantizing oscillations applied, of course, to line spectra as well. In contrast to the universality of blackbody radiation, the discrete lines of light emission and absorption varied immensely from one substance to the next. But the regularities evident even in the welter of the lines provided fertile matter for quantum conjectures. Molecular spectra turned into an all-important site of research during

The first Solvay Congress in 1911 assembled the pioneers of quantum theory. Seated (left to right): W. Nernst, M. Brillouin, E. Solvay, H. A. Lorentz, E. Warburg, J. Perrin, W. Wien, M. Curie, H. Poincaré. Standing (left to right): R. Goldschmidt, M. Planck, H. Rubens, A. Sommerfeld, F. Lindemann, M. de Broglie, M. Knudsen, F. Hasenöhrl, G. Hostelet, E. Herzen, J. Jeans, E. Rutherford, H. Kamerlingh Onnes, A. Einstein, P. Langevin. (From Cinquantenaire du Premier Conseil de Physique Solvay, 1911–1961).



The line spectrum of hydrogen. (From G. Herzberg, *Annalen der Physik*, 1927)

the quantum's second decade. Slower to take off, but ultimately even more productive, was the quantization of motions within the atom itself. Since no one had much sense of the atom's constitution, the venture into atomic spectra was allied to speculative model-building. Unsurprisingly, most of the guesses of the early 1910s turned out to be wrong. They nonetheless sounded out the possibilities. The orbital energy of electrons, their angular momentum (something like rotational inertia), or the frequency of their small oscillations about equilibrium: all these were fair game for quantization. The observed lines of the discrete spectrum could then be directly read off from the electrons' motions.

THE BOHR MODEL OF THE ATOM

It might seem ironic that Niels Bohr initially had no interest in spectra. He came to atomic structure indirectly. Writing his doctoral thesis on the electron theory of metals, Bohr had become fascinated by its failures and instabilities. He thought they suggested a new type of stabilizing force, one fundamentally different from those familiar in classical physics. Suspecting the quantum was somehow implicated, he could not figure out how to work it into the theory.

The intuition remained with him, however, as he transferred his postdoctoral attention from metals to Rutherford's atom. When it got started, the nuclear atom (its dense positive center circled by electrons) was simply one of several models on offer. Bohr began working on it during downtime in Rutherford's lab, thinking he could improve on its treatment of scattering. When he noticed that it ought to be unstable, however, his attention was captured for good. To stabilize the model by fiat, he set about imposing a quantum condition, according to the standard practice of the day. Only after a colleague directed his attention to spectra did he begin to think about their significance.

The famous Balmer series of hydrogen was manifestly news to Bohr. (See illustration above.) He soon realized, however, that he could fit it to his model—if he changed his model a bit. He reconceptualized light emission as a transition between discontinuous orbits, with the emitted frequency determined by $\Delta E = hf$. To get the

What Was Bohr Up To?

BOHR'S PATH to his atomic model was highly indirect. The rules of the game, as played in 1911–1912, left some flexibility in what quantum condition one imposed. Initially Bohr applied it to multielectron states, whose allowed energies he now broke up into a discrete spectrum. More specifically, he picked out their orbital frequencies to quantize. This is exactly what he would later proscribe in the final version of his model.

He rethought, however, in the face of the Balmer series and its simple numerical pattern

$$\mathbf{f_n} = \mathbf{R}\,(1/4 - 1/\mathbf{n}^2).$$

Refocusing on one electron and highlighting excited states, he reconceptualized light emission as a transition. The Balmer series then resulted from a tumble from orbit **n** to orbit 2; the Rydberg constant **R** could be determined in terms of **h**. However, remnants of the earlier model still appeared in his paper.

orbits' energies right, Bohr had to introduce some rather ad hoc rules. These he eventually justified by quantization of angular momentum, which now came in units of Planck's constant *h*. (He also used an interesting asymptotic argument that will resurface later.)

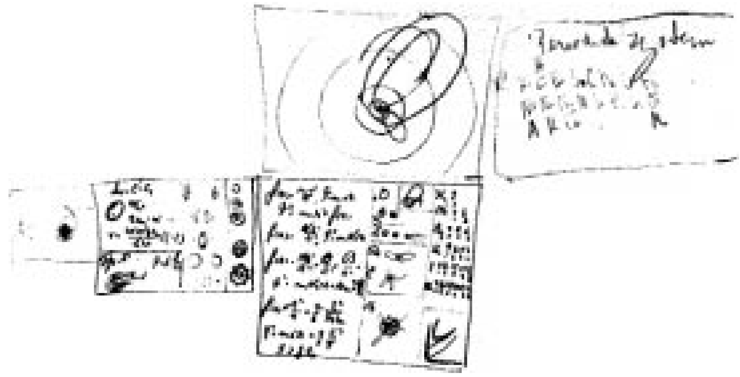
Published in 1913, the resulting picture of the atom was rather odd. Not only did a quantum condition describe transitions between levels, but the "stationary states," too, were fixed by nonclassical fiat. Electrons certainly revolved in orbits, but their frequency of revolution had nothing to do with the emitted light. Indeed, their oscillations were postulated *not* to produce radiation. There was no predicting when they might jump between levels. And transitions generated frequencies according to a quantum relation, but Bohr proved hesitant to accept anything like a photon.

The model, understandably, was not terribly persuasive—that is, until new experimental results began coming in on X rays, energy levels, and spectra. What really convinced the skeptics was a small modification Bohr made. Because the nucleus is not held fixed in space, its mass enters in a small way into the spectral frequencies. The calculations produced a prediction that fit to 3 parts in 100,000—pretty good, even for those days when so many numerical coincidences proved to be misleading.

The wheel made its final turn when Einstein connected the Bohr atom back to blackbody radiation. His famous papers on radiative transitions, so important for the laser (see following article by Charles Townes), showed the link among Planck's blackbody law, discrete energy levels, and quantized emission and absorption of radiation. Einstein further stressed that transitions could not be predicted in anything more than a probabilistic sense. It was in these same papers, by the way, that he formalized the notion of particle-like quanta.

THE OLD QUANTUM THEORY

What Bohr's model provided, like Einstein's account of specific heats, was a way to embed the quantum in a more general theory. In fact, the study of atomic structure would engender something plausibly called a quantum theory, one that began reaching towards a full-scale replacement for classical physics. The relation between the old and



Above: Bohr's lecture notes on atomic physics, 1921. (Original source: Niels Bohr Institute, Copenhagen. From Owen Gingerich, Ed., Album of Science: The Physical Sciences in the Twentieth Century*, 1989.)*

Left: Wilhelm Oseen, Niels Bohr, James Franck, Oskar Klein (left to right), and Max Born, seated, at the Bohr Festival in Göttingen, 1922. (Courtesy Emilio Segrè Visual Archives, Archive for the History of Quantum Physics)

the new became a key issue. For some features of Bohr's model preserved classical theories, while others presupposed their breakdown. Was this consistent or not? And why did it work?

By the late 1910s physicists had refined Bohr's model, providing a relativistic treatment of the electrons and introducing additional "quantum numbers." The simple quantization condition on angular momentum could be broadly generalized. Then the techniques of nineteenth-century celestial mechanics provided powerful theoretical tools. Pushed forward by ingenious experimenters, spectroscopic studies provided ever more and finer data, not simply on the basic line spectra, but on their modulation by electric and magnetic fields. And abetted by their elders, Bohr, Arnold Sommerfeld, and Max Born, a generation of youthful atomic theorists cut their teeth on such problems. The pupils, including Hendrik Kramers, Wolfgang Pauli, Werner Heisenberg, and Pascual Jordan, practiced a tightrope kind of theorizing. Facing resistant experimental data, they balanced the empirical evidence from the spectra against the ambiguities of the prescriptions for applying the quantum rules.

Within this increasingly dense body of work, an interesting strategy began to jell. In treating any physical system, the first task was to identify the possible classical motions. Then atop these classical motions, quantum conditions would be imposed. Quantization became a regular procedure, making continual if puzzling reference back to classical results. In another way, too, classical physics served as a touchstone. Bohr's famous "correspondence principle"

Paul Dirac and Werner Heisenberg in Cambridge, circa 1930. (Courtesy Emilio Segrè Visual Archives, Physics Today Collection)

first found application in his early papers, where it provided a deeper justification of his quantization condition. In the "classical limit," for large orbits with high quantum numbers and small differences in energy, the radiation from transitions between adjacent orbits should correspond to the classical radiation frequency. Quantum and classical results must match up. Employed with a certain Bohrian discrimination, the correspondence principle yielded detailed information about spectra. It also helped answer the question: How do we build up a true quantum theory?

Not that the solution was yet in sight. The old quantum theory's growing sophistication made its failures ever plainer. By the early 1920s the theorists found themselves increasingly in difficulties. No single problem was fatal, but their accumulation was daunting. This feeling of crisis was not entirely unspecific. A group of atomic theorists, centered on Bohr, Born, Pauli, and Heisenberg, had come to suspect that the problems went back to electron trajectories. Perhaps it was possible to abstract from the orbits? Instead they focused on transition probabilities and emitted radiation, since those might be more reliably knowable. "At the moment," Pauli still remarked in the spring of 1925, "physics is again very muddled; in any case, it is far too difficult for me, and I wish I were a movie comedian or something of the sort and had never heard of physics."

QUANTUM MECHANICS

Discontinuity, abstraction from the visualizable, a positivistic turn towards observable quantities: these preferences indicated one path to a full quantum theory. So, however, did their opposites. When in 1925–1926 a true quantum mechanics was finally achieved, two seemingly distinct alternatives were on offer. Both took as a leitmotif the relation to classical physics, but they offered different ways of working out the theme.

Heisenberg's famous paper of 1925, celebrated for launching the transformations to come, bore the title "On the Quantum-Theoretical Reinterpretation of Kinematical and Mechanical Relations." The point of departure was Bohr's tradition of atomic structure: discrete states remained fundamental, but now dissociated from intuitive representation. The transformative intent was even broader from the start. Heisenberg translated classical notions into quantum ones in the best correspondence-principle style. In his new quantum mechanics, familiar quantities behaved strangely; multiplication depended on the order of the terms. The deviations, however, were calibrated by Planck's constant, thus gauging the departure from classical normality.

Some greeted the new theory with elation; others found it unsatisfactory and disagreeable. For as elegant as Heisenberg's translation might be, it took a very partial view of the problems of the quantum. Instead of the quantum theory of atomic structure, one might also start from the wave-particle duality. Here another young theorist, Louis de Broglie, had advanced a speculative proposal in 1923 that Heisenberg and his colleagues had made little of. Thinking over the discontinuous, particle-like aspects of light, de Broglie suggested looking for continuous, wave-like aspects of electrons. His notion, while as yet ungrounded in experimental evidence, did provide surprising insight into the quantum conditions for Bohr's orbits. It also, by a sideways route, gave Erwin Schrödinger the idea for his brilliant papers of 1926.

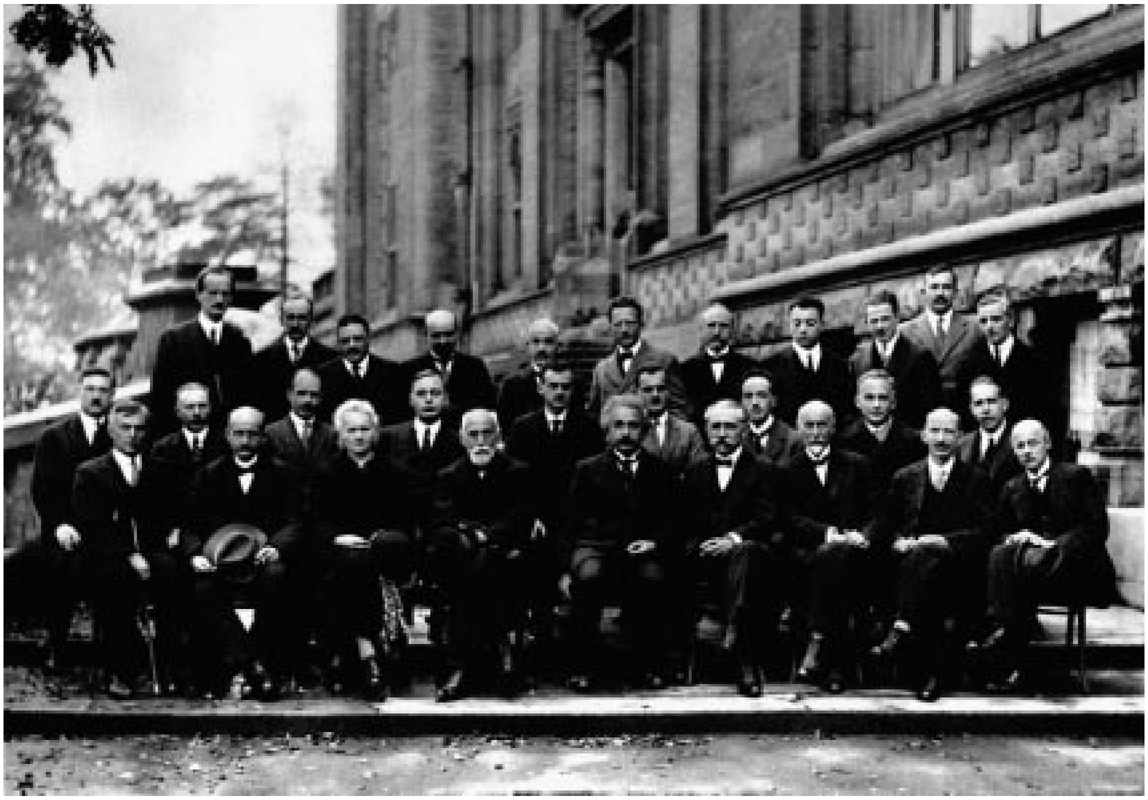
Imagining the discrete allowed states of any system of particles as simply the stable forms of continuous matter waves, Schrödinger sought connections to a well-developed branch of classical physics. The techniques of continuum mechanics allowed him to formulate an equation for his waves. It too was built around the constant h. But now the basic concepts were different, and so also the fundamental meaning. Schrödinger had a distaste for the discontinuity of Bohr's atomic models and the lack of intuitive picturability of Heisenberg's quantum mechanics. To his mind, the quantum did not imply any of these things. Indeed, it showed the opposite: that the apparent atomicity of matter disguised an underlying continuum.

The Quantum in Quantum Mechanics

ICONICALLY we now write Heisenberg's relations as

$$\mathbf{pq} - \mathbf{qp} = -\,\mathbf{ih}/2\pi.$$

Here **p** represents momentum and **q** represents position. For ordinary numbers, of course, **pq** equals **qp**, and so **pq** – **qp** is equal to zero. In quantum mechanics, this difference, called the commutator, is now measured by **h**. (The same thing happens with Heisenberg's uncertainty principle of 1927: $\Delta\mathbf{p}\Delta\mathbf{q} \geq \mathbf{h}/4\pi$.) The significance of the approach, and its rearticulation as a matrix calculus, was made plain by Max Born, Pascual Jordan, and Werner Heisenberg. Its full profundity was revealed by Paul Dirac.



Old faces and new at the 1927 Solvay Congress. The middle of the second row lines up Hendrik Kramers, Paul Dirac, Arthur Compton, and Louis de Broglie. Behind Compton stands Erwin Schrödinger, with Wolfgang Pauli and Werner Heisenberg next to each other behind Max Born. (From Cinquantenaire du Premier Conseil de Physique Solvay, 1911–1961)

Thus a familiar model connected to physical intuition, but constituting matter of some ill-understood sort of wave, confronted an abstract mathematics with seemingly bizarre variables, insistent about discontinuity and suspending space-time pictures. Unsurprisingly, the coexistence of alternative theories generated debate. The fact, soon demonstrated, of their mathematical equivalence did not resolve the interpretative dispute. For fundamentally different physical pictures were on offer.

In fact, in place of Schrödinger's matter waves and Heisenberg's uncompromising discreteness, a conventional understanding settled in that somewhat split the difference. However, the thinking of the old quantum theory school still dominated. Born dematerialized Schrödinger's waves, turning them into pure densities of probability for finding discrete particles. Heisenberg added his uncertainty principle, limiting the very possibility of measurement and undermining the law of causality. The picture was capped by Bohr's notion of complementarity, which sought to reconcile contradictory concepts like waves and particles.

Labeled the Copenhagen Interpretation after Bohr's decisive influence, its success (to his mind) led the Danish theorist to characterize quantum mechanics as a rational generalization of classical physics. Not everyone agreed that this was the end point. Indeed, Einstein, Schrödinger, and others were never reconciled. Even Bohr, Heisenberg, and Pauli expected further changes—though in a new domain, the quantum theory of fields, which took quantum mechanics to a higher degree of complexity. But their expectations of fundamental transformation in the 1930s and beyond, characterized by analogies to the old quantum theory, found little resonance outside of their circle.

Ironically enough, just as for their anti-Copenhagen colleagues, their demand for further rethinking did not make much headway. If the physical meaning of the quantum remained, to some, rather obscure, its practical utility could not be denied. Whatever lessons one took from quantum mechanics, it seemed to work. It not only incorporated gracefully the previous quantum phenomena, but opened the door to all sorts of new applications. Perhaps this kind of success was all one could ask for? In that sense, then, a quarter-century after Planck, the quantum had been built into the foundations of physical theory.

SUGGESTIONS FOR FURTHER READING

Olivier Darrigol, **From c-Numbers to q-Numbers: The Classical Analogy in the History of Quantum Theory** (Berkeley: U.C. Press, 1992).

Helge Kragh, **Quantum Generations: A History of Physics in the Twentieth Century** (Princeton, Princeton University Press, 1999).

Abraham Pais, **"Subtle is the Lord ...": The Science and the Life of Albert Einstein** (Oxford, Oxford University Press, 1982).

Helmut Rechenberg, "Quanta and Quantum Mechanics," in Laurie M. Brown, Abraham Pais, and Sir Brian Pippard, Eds., **Twentieth Century Physics**, Vol. 1 (Bristol and New York, Institute of Physics Publishing and American Institute of Physics Press, 1995), pp. 143-248.

The August 11, 2000, issue of **Science** (Vol. 289) contains an article by Daniel Kleppner and Roman Jackiw on "One Hundred Years of Quantum Physics." To see the full text of this article, go to http://www.sciencemag.org/cgi/content/full/289/5481/893.

THE LIGHT THAT SHIN

by CHARLES H. TOWNES

A Nobel laureate recounts the invention of the laser and the birth of quantum electronics.

ON JULY 21, 1969, astronauts Neil Armstrong and Edwin "Buzz" Aldrin set up an array of small reflectors on the moon, facing them toward Earth. At the same time, two teams of astrophysicists, one at the University of California's Lick Observatory and the other at the University of Texas's McDonald Observatory, were preparing small instruments on two big telescopes. Ten days later, the Lick team pointed its telescope at the precise location of the reflectors on the moon and sent a small pulse of power into the hardware they had added to it. A few days after that, the McDonald team went through the same steps. In the heart of each telescope, a narrow beam of extraordinarily pure red light emerged from a synthetic ruby crystal, pierced the sky, and entered the near vacuum of space. The two rays were still only a thousand yards wide after traveling 240,000 miles to illuminate the moon-based reflectors. Slightly more than a second after each light beam hit its target, the crews in California and Texas detected its faint reflection. The brief time interval between launch and detection of these light pulses permitted calculation of the distance to the moon to within an inch—a measurement of unprecedented precision.

The ruby crystal for each light source was the heart of a laser (an acronym for light amplification by stimulated emission of radiation), which is a device first demonstrated in 1960, just nine years earlier. A laser beam reflected from the moon to measure its distance is only one dramatic illustration of the spectacular quality of laser light. There are many other more mundane, practical uses such as in surveying land and grading roads, as well as myriad everyday uses—

Adapted by Michael Riordan from *How The Laser Happened: Adventures of a Scientist*, by Charles H. Townes. Reprinted by permission of Oxford University Press.

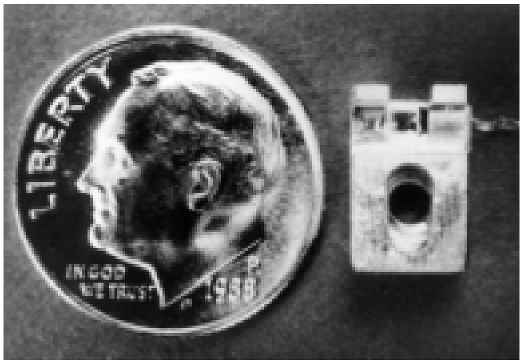
ES STRAIGHT

Lasers are commonly used in eye surgery to correct defective vision.

ranging from compact disc players to grocery-store checkout devices.

The smallest lasers are so tiny one cannot see them without a microscope. Thousands can be built on semiconductor chips. The biggest lasers consume as much electricity as a small town. About 45 miles from my office in Berkeley is the Lawrence Livermore National Laboratory, which has some of the world's most powerful lasers. One set of them, collectively called NOVA, produces ten individual laser beams that converge to a spot the size of a pinhead and generate temperatures of many millions of degrees. Such intensely concentrated energies are essential for experiments that can show physicists how to create conditions for nuclear fusion. The Livermore team hopes thereby to find a way to generate electricity efficiently, with little pollution or radioactive wastes.

For several years after the laser's invention, colleagues liked to tease me about it, saying, "That's a great idea, but it's a solution looking for a problem." The truth is, none of us who worked on the first lasers ever imagined how many uses there might eventually be. But that was not our motivation. In fact, many of today's practical technologies have resulted from basic scientific research done years to decades before. The people involved, motivated mainly by curiosity, often have little idea as to where their research will eventually lead.



An early small laser made of semiconducting material (right) compared with a U.S. dime.

LIKE THE TRANSISTOR, the laser and its progenitor the maser (an acronym for microwave amplification by stimulated emission of radiation) resulted from the application of quantum mechanics to electronics after World War II. Together with other advances, they helped spawn a new discipline in applied physics known since the late 1950s as "quantum electronics."

Since early in the twentieth century, physicists such as Niels Bohr, Louis de Broglie, and Albert Einstein learned how molecules and atoms absorb and emit light—or any other electromagnetic radiation—on the basis of the newly discovered laws of quantum mechanics. When atoms or molecules absorb light, one might say that parts of them wiggle back and forth or twirl with new, added energy. Quantum mechanics requires that they store energy in very specific ways, with precise, discrete levels of energy. An atom or a molecule can exist in either its ground (lowest) energy state or any of a set of higher (quantized) levels, but not at energies between those levels. Therefore they only absorb light of certain wavelengths, and no others, because the wavelength of light determines the energy of its individual photons (see box on right). As atoms or molecules drop from higher back to lower energy levels, they emit photons of the same energies or wavelengths as those they can absorb. This process is usually spontaneous, and this kind of light is normally emitted when these atoms or molecules glow, as in a fluorescent light bulb or neon lamp, radiating in nearly all directions.

Einstein was the first to recognize clearly, from basic thermodynamic principles, that if photons can be absorbed by atoms and boost them to higher energy states, then light can also prod an atom to give up its energy and drop down to a lower level. One photon hits the atom, and two come out. When this happens, the emitted photon takes off in precisely the same direction as the light that stimulated the energy loss, with the two waves exactly in step (or in the same "phase"). This "stimulated emission" results in coherent amplification, or amplification of a wave at exactly the same frequency and phase.

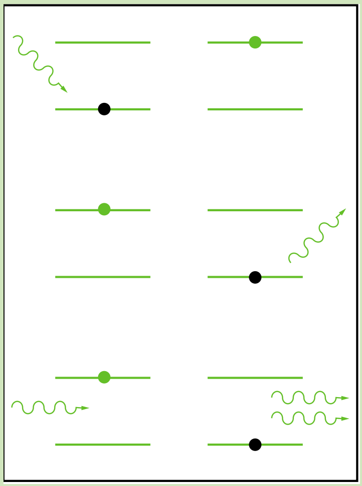
Both absorption and stimulated emission can occur simultaneously. As a light wave comes along, it can thus excite some atoms that are in lower energy states into higher states and, at the same time, induce some of those in higher states to fall back down to lower states. If there are more atoms in the upper states than in the lower states, more light is emitted than absorbed. In short, the light gets stronger. It comes out brighter than it went in.

The reason why light is usually absorbed in materials is that substances almost always have more atoms and molecules sitting in lower energy states than in higher ones: more photons are absorbed than emitted. Thus we do not expect to shine a light through a piece of glass and see it come out the other side brighter than it went in. Yet this is precisely what happens with lasers.

The trick in making a laser is to produce a material in which the energies of the atoms or molecules present have been put in a very abnormal condition, with more of them in excited states than in the

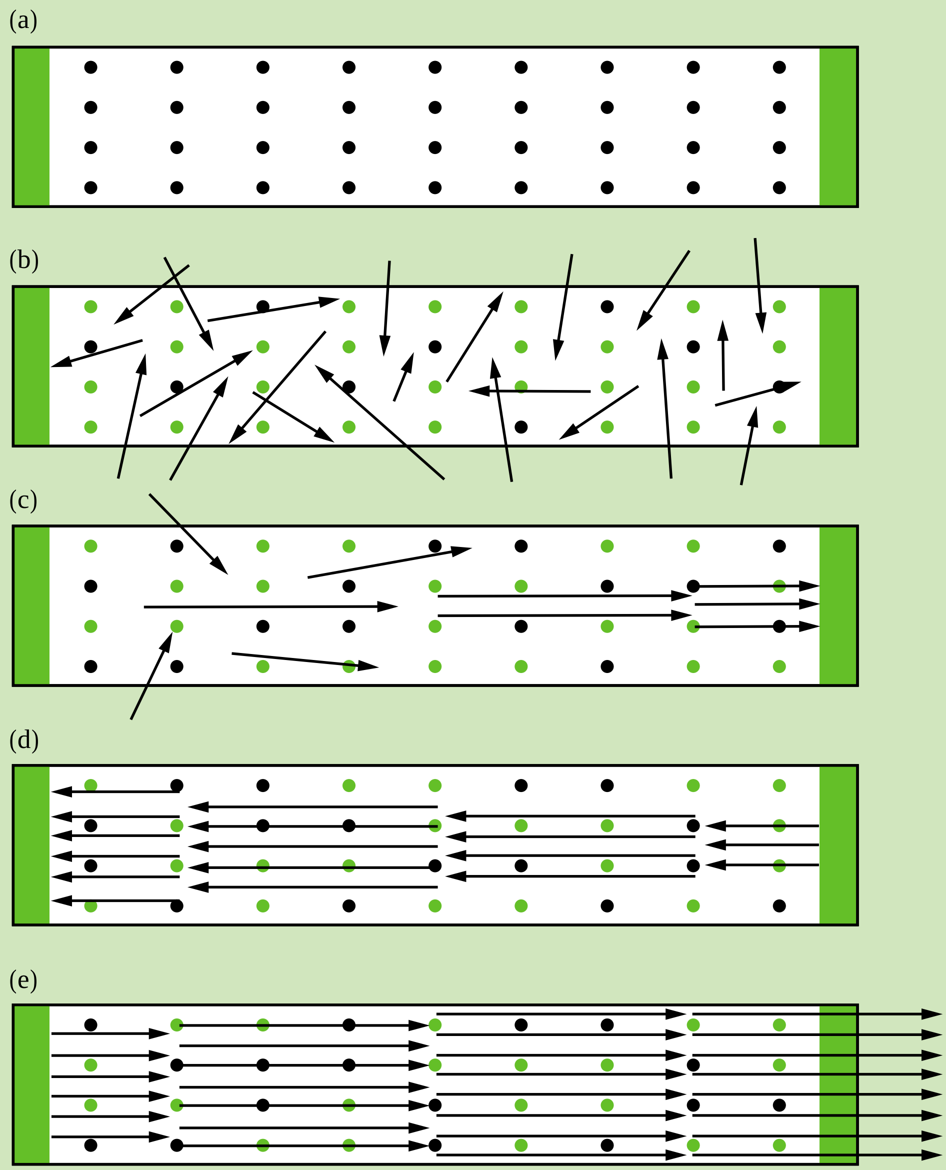
How Lasers Work

BECAUSE OF QUANTUM mechanics, atoms and molecules can exist only in discrete states with very specific values of their total energy. They change from one state to another by absorbing or emitting photons whose energies correspond to the difference between two such energy levels. This process, which generally occurs by an electron jumping between two adjacent quantum states, is illustrated in the accompanying drawings.



Stimulated emission of photons, the basis of laser operation, differs from the usual absorption and spontaneous emission. When an atom or molecule in the "ground" state absorbs a photon, it is raised to a higher energy state (top). This excited state may then radiate spontaneously, emitting a photon of the same energy and reverting back to the ground state (middle). But an excited atom or molecule can also be stimulated to emit a photon when struck by an approaching photon (bottom). In this case, there is now a second photon in addition to the stimulating photon; it has precisely the same wavelength and travels exactly in phase with the first.

Lasers involve many atoms or molecules acting in concert. The set of drawings (right) illustrates laser action in an optical-quality crystal, producing a cascade of photons emitted in one direction.



(a) Before the cascade begins, the atoms in the crystal are in their ground state. (b) Light pumped in and absorbed by these atoms raises most of them to the excited state. (c) Although some of the spontaneously emitted photons pass out of the crystal, the cascade begins when an excited atom emits a photon parallel to the axis of the crystal. This photon stimulates another atom to contribute a second photon, and (d) the process continues as the cascading photons are reflected back and forth between the parallel ends of the crystal. (e) Because the right-hand end is only partially reflecting, the beam eventually passes out this end when its intensity becomes great enough. This beam can be very powerful.

None of us who worked on the first lasers ever imagined how many uses there might eventually be. Many of today's practical technologies have resulted from basic scientific research done years to decades before.

ground, or lower, states. A wave of electromagnetic energy of the proper frequency traveling through such a peculiar substance will pick up rather than lose energy. The increase in the number of photons associated with this wave represents amplification—light amplification by stimulated emission of radiation.

If this amplification is not very large on a single pass of the wave through the material, there are ways to beef it up. For example, two parallel mirrors—between which the light is reflected back and forth, with excited molecules (or atoms) in the middle—can build up the wave. Getting the highly directional laser beam out of the device is just a matter of one mirror being made partially transparent, so that when the internally reflecting beam gets strong enough, a substantial amount of its power shoots right on through one end of the device.

The way this manipulation of physical laws came about, with the many false starts and blind alleys on the way to its realization, is the subject of my book, *How the Laser Happened*. Briefly summarized in this article, it also describes my odyssey as a scientist and its unpredictable and perhaps natural path to the maser and laser. This story is interwoven with the way the field of quantum electronics grew, rapidly and strikingly, owing to a variety of important contributors, their cooperation and competitiveness.

DURING THE LATE 1940s and early 1950s, I was examining molecules with microwaves at Columbia University—doing microwave spectroscopy. I tried to find a way to generate waves shorter than those produced by the klystrons and magnetrons developed for radar in World War II. One day I suddenly had an idea—use molecules and the stimulated emission from them. With graduate student Jim Gordon and postdoc Herb Zeiger, I decided to experiment first with ammonia (NH_3) molecules, which emit radiation at a wavelength of about 1 centimeter. After a couple of years of effort, the idea worked. We christened this device the "maser." It proved so interesting that for a while I put off my original goal of trying to generate even shorter wavelengths.

In 1954, shortly after Gordon and I built our second maser and showed that the frequency of its microwave radiation was indeed remarkably pure, I visited Denmark and saw Niels Bohr. As we were walking along the street together, he asked me what I was doing. I described the maser and its amazing performance.

"But that is not possible!" he exclaimed. I assured him it was.

Similarly, at a cocktail party in Princeton, New Jersey, the Hungarian mathematician John von Neumann asked what I was working on. I told him about the maser and the purity of its frequency.

"That can't be right!" he declared. But it was, I replied, telling him it had already been demonstrated.

Such protests were not offhand opinions about obscure aspects of physics; they came from the marrow of these men's bones. Their objections were founded on principle—the Heisenberg uncertainty principle. A central tenet of quantum mechanics, this principle is among the core achievements that occurred during a phenomenal burst of creativity in the first few decades of the twentieth century. As its name implies, it describes the impossibility of achieving absolute knowledge of all the aspects of a system's condition. There is a price to be paid in attempting to measure or define one aspect of a specific particle to very great exactness. One must surrender knowledge of, or control over, some other feature.

A corollary of this principle, on which the maser's doubters stumbled, is that one cannot measure an object's frequency (or energy) to great accuracy in an arbitrarily short time interval. Measurements made over a finite period of time automatically impose uncertainty on the observed frequency.

To many physicists steeped in the uncertainty principle, the maser's performance, at first blush, made no sense at all. Molecules race through its cavity, spending so little time there—about one ten-thousandth of a second—that it seemed impossible for the frequency of the output microwave radiation to be so narrowly defined. Yet that is exactly what happens in the maser.

There is good reason that the uncertainty principle does not apply so simply here. The maser (and by analogy, the laser) does not tell you anything about the energy or frequency of any specific molecule. When a molecule (or atom) is stimulated to radiate, it must produce exactly the same frequency as the stimulating radiation. In addition, this radiation represents the average of a large number of molecules (or atoms) working together. Each individual molecule remains anonymous, not accurately measured or tracked. The precision arises from factors that mollify the apparent demands of the uncertainty principle.

I am not sure that I ever did convince Bohr. On that sidewalk in Denmark, he told me emphatically that if molecules zip through the maser so quickly, their emission lines must be broad. After I persisted, however, he relented.

"Oh, well, yes," he said; "Maybe you are right." But my impression was that he was just trying to be polite to a younger physicist.

After our first chat at that Princeton party, von Neumann wandered off and had another drink. In about fifteen minutes, he was back.

"Yes, you're right," he snapped. Clearly, he had seen the point.

NOVA, the world's largest and most powerful laser, at the Lawrence Livermore National Laboratory in California. Its 10 laser beams can deliver 15 trillion watts of light in a pulse lasting 3 billionths of a second. With a modified single beam, it has produced 1,250 trillion watts for half a trillionth of a second. (Courtesy Lawrence Livermore National Laboratory)

He seemed very interested, and he asked me about the possibility of doing something similar at shorter wavelengths using semiconductors. Only later did I learn from his posthumous papers, in a September 1953 letter he had written to Edward Teller, that he had already proposed producing a cascade of stimulated infrared radiation in semiconductors by exciting electrons with intense neutron bombardment. His idea was almost a laser, but he had not thought of employing a reflecting cavity nor of using the coherent properties of stimulated radiation.

The development of the laser followed no script except to hew to the nature of scientists groping to understand, to explore, and to create.

IN THE LATE SUMMER of 1957, I felt it was high time I moved on to the original goal that fostered the maser idea: oscillators that work at wavelengths appreciably shorter than 1 millimeter, beyond what standard electronics could achieve. For some time I had been thinking off and on about this goal, hoping that a great idea would pop into my head. But since nothing had spontaneously occurred to me, I decided I had to take time for concentrated thought.

A major problem to overcome was that the rate of energy radiation from a molecule increases as the fourth power of the frequency. Thus to keep molecules or atoms excited in a regime to amplify at a wavelength of, say, 0.1 millimeter instead of 1 centimeter requires an increase in pumping power by many orders of magnitude. Another problem was that for gas molecules or atoms, Doppler effects increasingly broaden the emission spectrum as the wavelength gets smaller. That means there is less amplification per molecule available to drive any specific resonant frequency inside a cavity.

As I played with the variety of possible molecular and atomic transitions, and the methods of exciting them, what is well-known today suddenly became clear to me: it is just as easy, and probably easier, to go right on down to really short wavelengths—to the near-infrared or even optical regions—as to go down one smaller step at a time. This was a revelation, like stepping through a door into a room I did not suspect existed.

The Doppler effect does indeed increasingly smear out the frequency of response of an atom (or molecule) as one goes to shorter wavelengths, but there is a compensating factor that comes into play. The number of atoms required to amplify a wave by a given amount does not increase, because atoms give up their quanta more readily at higher frequencies. And while the power needed to keep a certain number of atoms in excited states increases with the frequency, the total power required—even to amplify visible light—is not necessarily prohibitive.

Not only were there no clear penalties in such a leapfrog to very short wavelengths or high frequencies, this approach offered big advantages. In the near-infrared and visible regions, we already had plenty of experience and equipment. By contrast, wavelengths near 0.1 mm and techniques to handle them were relatively unknown. It was time to take a big step.

Still, there remained another major concern: the resonant cavity. To contain enough atoms or molecules, the cavity would have to be much longer than the wavelength of the radiation—probably thousands of times longer. This meant, I feared, that no cavity could be very selective for one and only one frequency. The great size of the cavity, compared to a single wavelength, meant that many closely spaced but slightly different wavelengths would resonate.

By great good fortune, I got help and another good idea before I proceeded any further. I had recently begun a consulting job at Bell Labs, where my brother-in-law and former postdoc Arthur Schawlow was working. I naturally told him that I had been thinking about such optical masers, and he was very interested because he had also been thinking in that very direction.

We talked over the cavity problem, and Art came up with the solution. I had been considering a rather well-enclosed cavity, with mirrors on the ends and holes in the sides only large enough to provide a way to pump energy into the gas and to kill some of the directions in which the waves might bounce. He suggested instead that we use just two plates, two simple mirrors, and leave off the sides altogether. Such arrangements of parallel mirrors were already used at the time in optics; they are called Fabry–Perot interferometers.

Art recognized that without the sides, many oscillating modes that depend on internal reflections would eliminate themselves. Any wave hitting either end mirror at an angle would eventually walk itself out of the cavity—and so not build up energy. The only modes that could survive and oscillate, then, would be waves reflected exactly straight back and forth between the two mirrors.

More detailed studies showed that the size of the mirrors and the distance between them could even be chosen so that only one frequency would be likely to oscillate. To be sure, any wavelength that fit an exact number of times between the mirrors could resonate in such a cavity, just as a piano string produces not just one pure frequency but also many higher harmonics. In a well-designed system, however, only one frequency will fall squarely at the transition energy of the medium within it. Mathematically and physically, it was "neat."

Art and I agreed to write a paper jointly on optical masers. It seemed clear that we could actually build one, but it would take time. We spent nine months working on and off in our spare time to write the paper. We needed to clear up the engineering and some specific details, such as what material to use, and to clarify the theory. By August 1958 the manuscript was complete, and the Bell Labs patent lawyers told us that they had done their job protecting its ideas. *The Physical Review* published it in the December 15, 1958, issue.

In September 1959 the first scientific meeting on quantum electronics and resonance phenomena occurred at the Shawanga Lodge in New York's Catskill Mountains. In retrospect, it represented the formal birth of the maser and its related physics as a distinct subdiscipline. At that meeting Schawlow delivered a general talk on optical masers.

Listening with interest was Theodore Maiman from the Hughes Research Laboratories in Culver City, California. He had been working with ruby masers and says he was already thinking about using ruby as the medium for a laser. Ted listened closely to the rundown on the possibility of a solid-state ruby laser, about which Art was not too hopeful. "It may well be that more suitable solid materials can be found," he noted, "and we are looking for them."

James Gordon, Nikolai Basov, Herbert Zeiger, Alexander Prokhorov, and author Charles Townes (left to right) attending the first international conference on quantum electronics in 1959.

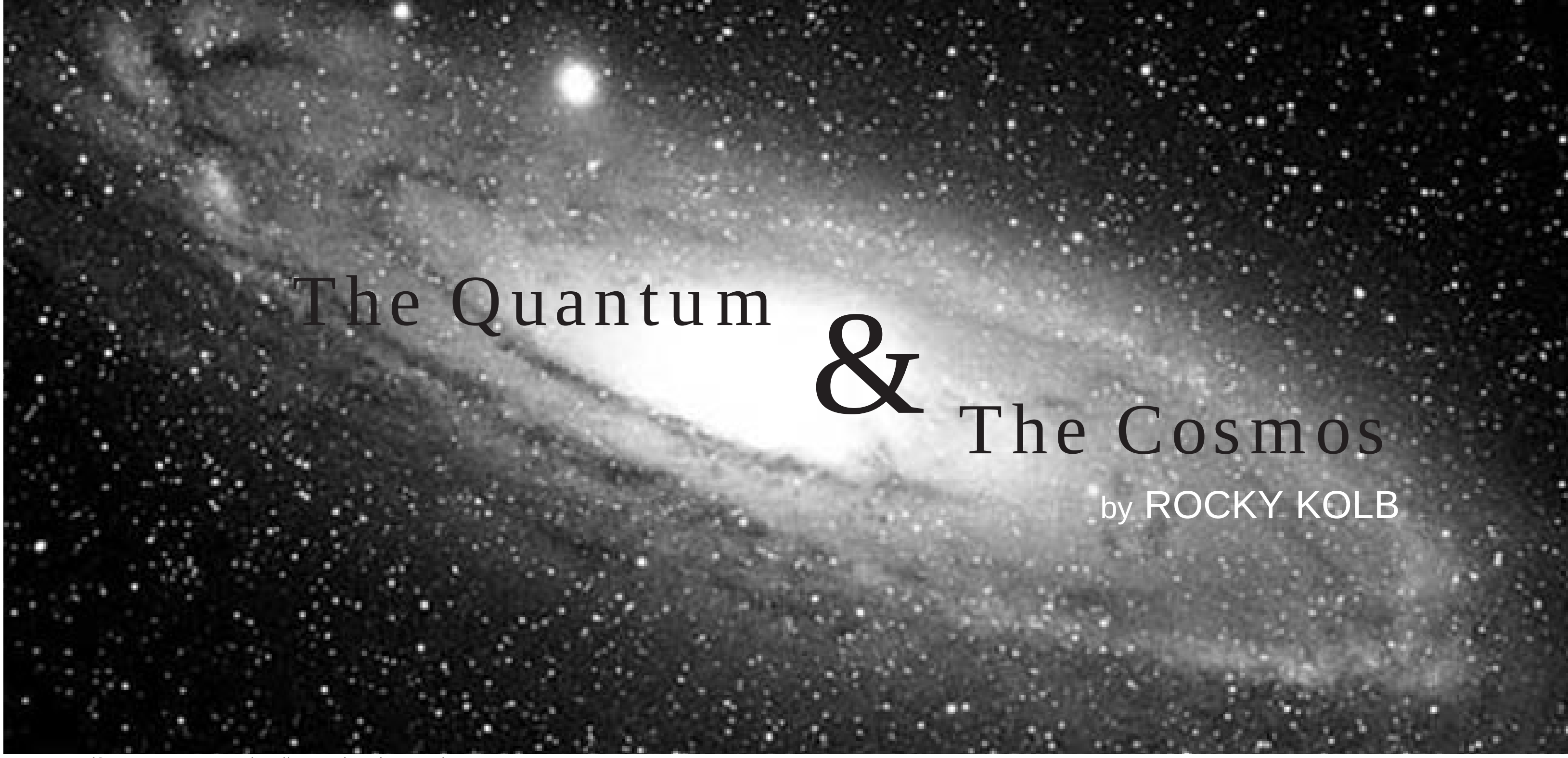
Maiman felt that Schawlow was far too pessimstic and left the meeting intent on building a solid-state ruby laser. In subsequent months Ted made striking measurements on ruby, showing that its lowest energy level could be partially emptied by excitation with intense light. He then pushed on toward still brighter excitation sources. On May 16, 1960, he fired up a flash lamp wrapped around a ruby crystal about 1.5 cm long and produced the first operating laser.

The evidence that it worked was somewhat indirect. The Hughes group did not set it up to shine a spot of light on the wall. No such flash of a beam had been seen, which left room for doubt about just what they had obtained. But the instruments had shown a substantial change in the fluorescence spectrum of the ruby; it became much narrower, a clear sign that emission had been stimulated, and the radiation peaked at just the wavelengths that were most favored for such action. A short while later, both the Hughes researchers and Schawlow at Bell Labs independently demonstrated powerful flashes of directed light that made spots on the wall—clear intuitive proof that a laser is indeed working.

IT IS NOTEWORTHY that almost all lasers were first built in industrial labs. Part of the reason for industry's success is that once its importance becomes apparent, industrial laboratories can devote more resources and concentrated effort to a problem than can a university. When the goal is clear, industry can be effective. But the first lasers were invented and built by young scientists recently hired after their university research in the field of microwave and radio spectroscopy—students of Willis Lamb, Polykarp Kusch, and myself, who worked together in the Columbia Radiation Laboratory, and of Nicholas Bloembergen at Harvard. The whole field of quantum electronics grew out of this approach to physics.

The development of the maser and laser followed no script except to hew to the nature of scientists groping to understand, explore and create. As a striking example of how important technology applied to human interests can grow out of basic university research, the laser's development fits a pattern that could not have been predicted in advance.

What research planner, wanting a more intense light source, would have started by studying molecules with microwaves? What industrialist, looking for new cutting and welding devices, or what doctor, wanting a new surgical tool as the laser has become, would have urged the study of microwave spectroscopy? The whole field of quantum electronics is truly a textbook example of broadly applicable technology growing unexpectedly out of basic research.



(Courtesy Jason Ware, http://www.galaxyphoto.com)

The Quantum & The Cosmos

by ROCKY KOLB

"When one tugs at a single thing in Nature, he finds it hitched to the rest of the Universe."

—John Muir

ONE NORMALLY THINKS that quantum mechanics is only relevant on submicroscopic scales, operating in the domain of atomic, nuclear, and particle physics. But if our most exciting ideas about the evolution of the early Universe are correct, then the imprint of the quantum world is visible on astronomical scales. The possibility that quantum mechanics shaped the largest structures in the Universe is one of the theories to come from the marriage of the quantum and the cosmos.

WHAT'S OUT THERE?

On a dark clear night the sky offers much to see. With the unaided eye one can see things in our solar system such as planets, as well as extrasolar objects like stars. Nearly everything visible by eye resides within our own Milky Way Galaxy. But with a little patience and skill it's possible to find a few extra-galactic objects. The Andromeda Galaxy, 2.4 million light-years distant, is visible as a faint nebulous region, and from the Southern Hemisphere two small nearby galaxies (if 170,000 light-years can be considered nearby), the Magellanic Clouds, can also be seen with the unaided eye.

While the preponderance of objects seen by eye are galactic, the view through large telescopes reveals the universe beyond the Milky Way. Even with the telescopes of the nineteenth century, the great British astronomer Sir William Herschel discovered about 2,500 galaxies, and his son, Sir John Herschel, discovered an additional thousand (although neither of the Herschels knew that the objects they discovered were extragalactic). As

Galaxies fill the Hubble Deep Field, one of the most distant optical views of the Universe. The dimmest ones, some as faint as 30th magnitude (about four billion times fainter than stars visible to the unaided eye), are very distant and represent what the Universe looked ike in the extreme past, perhaps less than one billion years after the Big Bang. To make this Deep Field image, astronomers selected an uncluttered area of the sky in the constellation Ursa Major and pointed the Hubble Space Telescope at a single spot for 10 days accumulating and combining many separate exposures. With each additional exposure, fainter objects were revealed. The final result can be used to explore the mysteries of galaxy evolution and the early Universe. (Courtesy R. Williams, The HDF Team, STScI, and NASA)

astronomers built larger telescopes and looked deeper into space, the number of known galaxies grew. Although no one has ever bothered to count, astronomers have identified about four million galaxies. And there are a lot more out there!

Our deepest view into the Universe is the Hubble Deep Field. The result of a 10-day exposure of a very small region of the sky by NASA's Hubble Space Telescope, the Hubble Deep Field reveals a universe full of galaxies as far as Hubble's eye can see (photo above). If the Space Telescope could take the time to survey the entire sky to the depth of the Deep Field, it would find more than 50 billion galaxies.

Although large galaxies contain at least 100 billion stars and stretch across 100,000 light-years or more of space, they aren't the biggest things in the Universe. Just as stars are part of galaxies, galaxies are part of larger structures.

Many galaxies are members of groups containing a few dozen to a hundred galaxies, or even larger assemblages known as clusters, containing several thousand galaxies. Clusters of galaxies are part of even larger associations called superclusters, containing dozens of clusters spread out over 100 million light-years of space. Even superclusters may not be the largest things in the Universe. The largest surveys of the Universe suggest to some astronomers that galaxies are organized on two-dimensional sheet-like structures, while others believe that galaxies lie along extended one-dimensional filaments. The exact nature of how galaxies are arranged in the Universe is still a matter of debate among cosmologists. A picture of the arrangement of galaxies on the largest scales is only now emerging.

Not all of the Universe is visible to the eye. In addition to patterns in the arrangement of matter in the visible Universe, there is also a structure to the background radiation.

The Universe is awash in a thermal bath of radiation, with a temperature of three degrees above absolute zero (3 K or –270 C). Invisible to the human eye, the background radiation is a remnant of the hot primeval fireball. First discovered in 1965 by Arno Penzias and Robert Wilson, it is a fundamental prediction of the Big Bang theory.

Soon after Penzias and Wilson discovered the background radiation, the search began for variations in the temperature of the universe. For nearly 30 years, astrophysicists searched in vain for regions of the distant Universe that were hotter or colder than average. It was not until 1992 that a team of astronomers using the Cosmic Background Explorer Satellite (COBE) discovered an intrinsic pattern in the temperature of the Universe. Since the time of the COBE discovery, a pattern of temperature variations has been measured with increasing precision by dozens of balloon-borne and terrestrial observations. A new era of precision cosmological observations is starting. Sometime in 2001 NASA will launch a new satellite, the Microwave Anisotropy Probe (MAP), and sometime in 2007 the European Space Agency will launch an even more ambitious effort, the Planck Explorer, to study temperature variations in the cosmic background radiation.

Even if our eyes were sensitive to microwave radiation, we would have a hard time discerning a pattern of temperature fluctuations since the hottest and coldest regions of the background radiation are only about one-thousandth of a percent hotter and colder than average.

Although small in magnitude, the background temperature fluctuations are large in importance since they give us a snapshot of structure in the Universe when the background photons last scattered, about 300,000 years after the Bang.

WHY IS IT THERE?

A really good answer to a deep question usually leads to even deeper questions. Once we discover what's in the Universe, a deeper question arises: Why is it there? Why are stars arranged into galaxies, galaxies into clusters, clusters into superclusters, and so on? Why are there small variations in the temperature of the Universe?

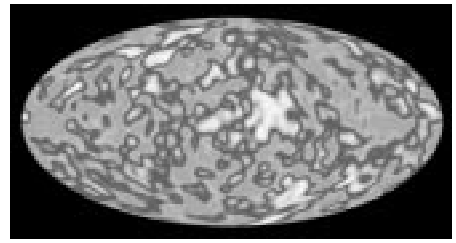
Part of the answer involves gravity. Everything we see in the Universe is the result of gravity. Every time you see a star the imprint of gravity is shining at you. Today we observe new stars forming within giant interstellar gas clouds, such as those found at the center of the Orion Nebula just 1,500 light-years away (see photo on next page).

Interstellar clouds are not smooth and uniform; they contain regions where the density of material is larger than in surrounding regions. The dense regions within the clouds are the seeds around which stars grow through the irresistible force of gravity. The dense regions pull in nearby material through the force of gravity, which compresses the material until it becomes hot and dense enough for nuclear reactions to commence and form stars.

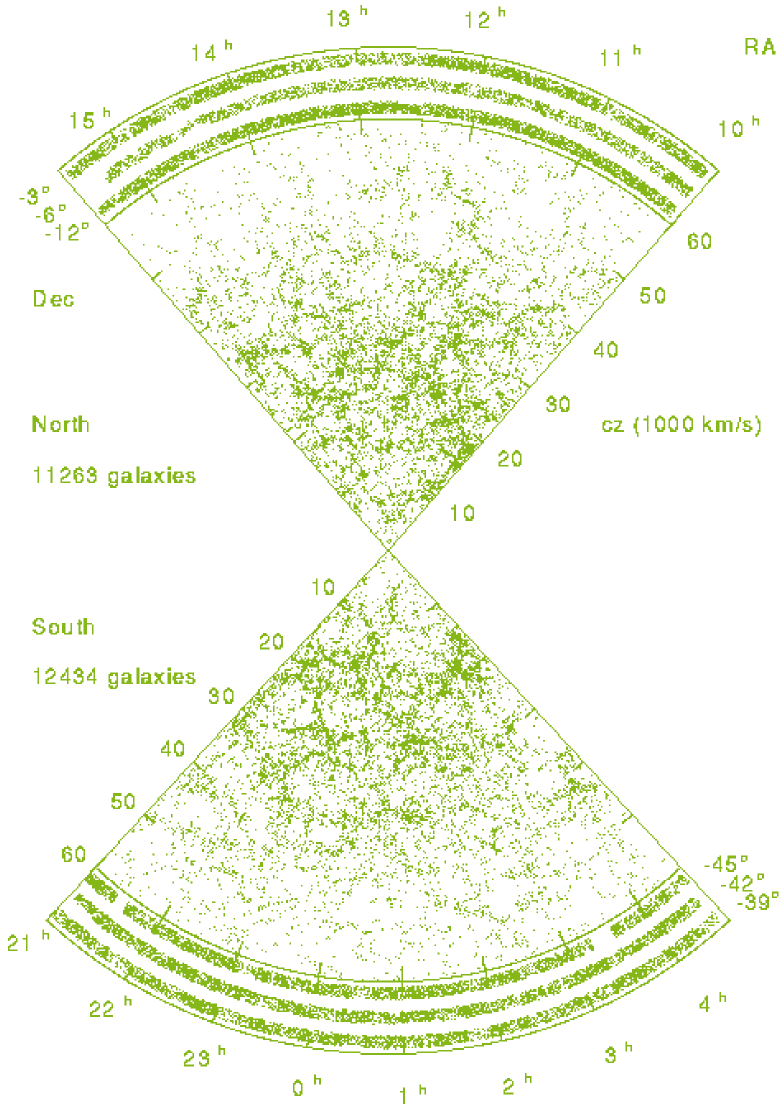
About five billion years ago in our little corner of the Milky Way, gravity started to pull together gas and dust to form our solar system. This fashioning of structure in our local neighborhood is just a small part of a process that started about 12 billion years ago on a grander scale throughout the Universe.

For the first 300 centuries after the Big Bang, the Universe expanded too rapidly for gravity to fashion structure. Finally, 30,000 years after the Bang (30,000 AB), the expansion had slowed enough for gravity to begin the long relentless process of pulling together matter to form the Universe we see today.

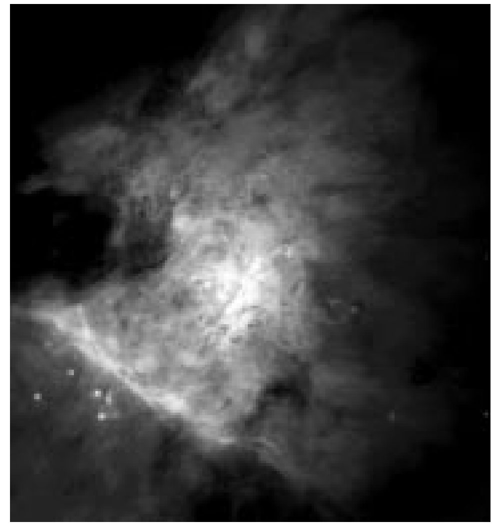
We are quite confident that gravity shaped the Universe because astrophysicists can simulate in a matter of days what Nature required 12 billion years to accomplish. Starting with the Universe as it existed 30,000 AB, large supercomputers can



The microwave radiation from the sky, as seen by COBE. The radiation has an average temperature of 2.73 degrees Centigrade above absolute zero. Here the dark and light spots are 1 part in 100,000 warmer or colder than the rest. They reveal gigantic structures stretching across enormous regions of space. The distinct regions of space are believed to be the primordial seeds produced during the Big Bang. Scientists believe these anomalous regions evolved into the galaxies and larger structures of the present-day Universe. (Courtesy Lawrence Berkeley Laboratory and NASA)



Galaxies and galaxy clusters are not evenly distributed throughout the Universe, instead they are arranged in clusters, filaments, bubbles, and vast sheet-like projections that stretch across hundreds of millions of light-years of space. The goal of the Las Campanas Redshift Survey is to provide a large galaxy sample which permits detailed and accurate analyses of the properties of galaxies in the local universe. This map shows a wedge through the Universe containing more than 20,000 galaxies (each dot is a galaxy). (Courtesy Las Campanas Redshift Survey)



The Orion nebula, one of the nearby star-forming regions in the Milky Way galaxy. (Courtesy StScI and NASA)

calculate how small primordial seeds grew to become the giant galaxies, clusters of galaxies, superclusters, walls, and filaments we see throughout the Universe.

Gravity alone cannot be the final answer to the question of why matter in the Universe has such a rich and varied arrangement. For the force of gravity to pull things together requires small initial seeds where the density is larger than the surrounding regions. In a very real sense, the fact there is anything in the Universe at all is because there were primordial seeds in the Universe. While the force of gravity is inexorable, structure cannot grow without the seeds to cultivate. Just as though there wouldn't be any seeds to trigger star formation within the Orion Nebula if the gas and dust were perfectly uniform, structure would never have formed if the entire Universe was completely uniform. Without primordial seeds in the Universe 30,000 AB, gravity would be unable to shape the Universe into the form we now see. A seedless universe would be a pretty boring place to live, because matter would remain perfectly uniform rather than assembling into discrete structures.

The pattern of structure we see in the Universe today reflects the pattern of initial seeds. Seeds have to be inserted by hand into the computer simulations of the formation of structure. Since the aim of cosmology is to understand the structure of the Universe on the basis of physical laws, we just can't end the story by saying structure exists because there were primordial seeds. For a complete answer to the questions of why are there things in the Universe, we have to know what planted the primordial seeds.

In the microworld of subatomic physics, there is an inherent uncertainty about the positions and energies of particles. According to the uncertainty principle, energy isn't always conserved—it can be violated for a brief period of time. Because quantum mechanics applies to the microworld, only tiny amounts of energy are involved, and the time during which energy is out of balance is exceedingly short.

One of the consequences of the uncertainty principle is that a region of seemingly empty space is not really empty, but is a seething froth in which every sort of fundamental particle pops out of empty space for a brief instant before annihilating with its antiparticle and disappearing.

Empty space only looks like a quiet, calm place because we can't see Nature operating on submicroscopic scales. In order to see these quantum fluctuations we would have to take a small region of space and blow it up in size. Of course that is not possible in any terrestrial laboratory, so to observe the quantum fluctuations we have to use a laboratory as large as the entire Universe.

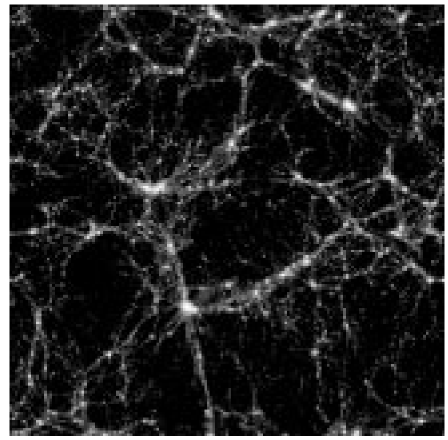
In the early-Universe theory known as inflation, space once exploded so rapidly that the pattern of microscopic vacuum quantum fluctuations became frozen into the fabric of space. The expansion of the Universe stretched the microscopic pattern of quantum fluctuations to astronomical size.

Much later, the pattern of what once were quantum fluctuations of the vacuum appear as small fluctuations in the mass density of the Universe and variations in the temperature of the background radiation.

If this theory is correct, then seeds of structure are nothing more than patterns of quantum fluctuations from the inflationary era. In a very real sense, quantum fluctuations would be the origin of everything we see in the Universe.

When viewing assemblages of stars in galaxies or galaxies in galactic clusters, or when viewing the pattern of fluctuations in the background radiation, you are actually *seeing* quantum fluctuations. Without the quantum world, the Universe would be a boring place, devoid of structures like galaxies, stars, planets, people, poodles, or petunias.

This deep connection between the quantum and the cosmos may be the ultimate expression of the true unity of science. The study of the very large leads to the study of the very small. Or as the great American naturalist John Muir stated, "When one tugs at a single thing in Nature, he finds it hitched to the rest of the Universe."



One of several computer simulations of the large-scale structure of the Universe (spatial distribution of galaxies) carried out by the VIRGO collaboration. These simulations attempt to understand the observed large-scale structure by testing various physics models. (Courtesy VIRGO Collaboration)

For Additional Information on the Internet

Rocky Kolb. http://www-astro-theory.fnal.gov/Personal/rocky/welcome.html

Jason Ware. http://www.galaxyphoto.com

Hubble Space Telescope Public Pictures. http://oposite.stsci.edu/pubinfo/Pictures.html

NASA Image eXchange. http://nix.nasa.gov/

VIRGO Consortium. http://star-www.dur.ac.uk/~frazerp/virgo/virgo.html

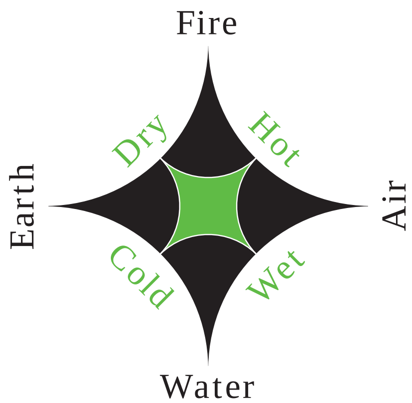
COBE Sky Map. http://www.lbl.gov/LBL-PID/George-Smoot.html

Las Campanas Redshift Survey. http://manaslu.astro.utoronto.ca/~lin/lcrs.html

Sloan Digital Sky Survey. http://www.sdss.org

Getting to Know

by ROBERT L. JAFFE



Humankind has wondered since the beginning of history what are the fundamental constituents of matter. Today's list includes about 25 elementary particles. Tomorrow's list promises to be longer still, with no end in sight.

THE URGE TO REDUCE THE FORMS of matter to a few elementary constituents must be very ancient. By 450 BCE, Empedocles had already developed or inherited a "standard model" in which everything was composed of four elements—Air, Earth, Fire, and Water. Thinking about the materials available to him, this is not a bad list. But as a predictive model of Nature, it has some obvious shortcomings. Successive generations have evolved increasingly sophisticated standard models, each with its own list of "fundamental" constituents. The length of the list has fluctuated over the years, as shown on the next page. The Greeks are actually tied for the minimum with four. The chemists of the 19th century and the particle physicists of the 1950s and 1960s pushed the number up toward 100 before some revolutionary development reduced it dramatically. Today's list includes about 25 elementary particles, though it could be either higher or lower depending on how you count. Tomorrow's list—the product of the next generation of accelerators—promises to be longer still, with no end in sight. In fact, modern speculations always seem to increase rather than decrease the number of fundamental constituents. Superstring theorists dream of unifying all the forces and forms of matter into a single essence, but so far they have little clue how the diversity of our observed world would devolve from this perfect form. Others have pointed out that Nature at the shortest distances and highest energies might be quite random and chaotic, and that the forces we feel and the particles we observe are special only in that they persist longer and propagate further than all the rest.

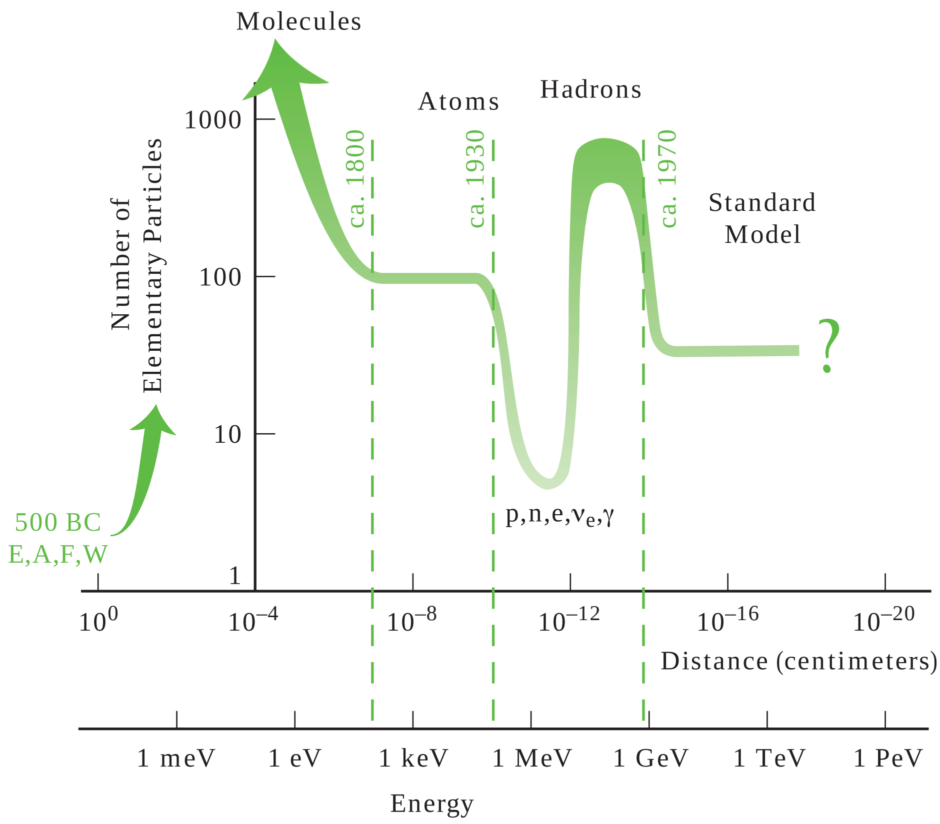
Two lessons stand out in this cartoon history. First, what serves as a "fundamental constituent" changes with time and depends on what sorts of questions one asks. The older

Your Constituents

models are not really inferior to today's Standard Model within the context of the world they set out to describe. And, second, there always seems to be another layer. In the early years of the 21st century particle physicists will be probing deeply into the physics of the current Standard Model of particle physics with new accelerators like the B-factories of SLAC and KEK and the Large Hadron Collider at CERN. Now seems like a good time to reflect on what to expect.

It is no accident, nor is it a sign of our stupidity, that we have constructed "atomic" descriptions of Nature on several different scales only to learn that our "atoms" were composed of yet more fundamental constituents. Quantum mechanics itself gives rise to this apparently layered texture of Nature. It also gives us very sophisticated tools and tests with which to probe our constituents for substructure. Looking back at the "atoms" of previous generations, we can see where the hints of substructure first appeared and how our predecessors were led to the next layer. Looking forward from our present crop of elementary particles, we see some suggestions of deeper structure beneath, but—tantalizingly—other signs suggest that today's fundamental constituents, numerous as they

A schematic history of the concept of an elementary constituent, from the four elements of the Greeks to today's Standard Model. The number has gone up and down over the years.



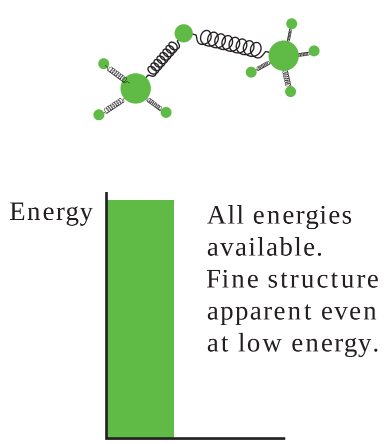
are, may be more fundamental than yesterday's.

BEFORE LOOKING at where we are today, let's take a brief tour of the two most useful "atomic" descriptions of the past: the standard models of chemistry and nuclear physics, shown below. Both provide very effective descriptions of phenomena within their range of applicability. Actually the term "effective" has a technical meaning here. For physicists an "effective theory" is one based on building blocks known not to be elementary, but which can be treated as if they were, in the case at hand. "Effective" is the right word because it means both "useful" and "standing in place of," both of which apply in this case. The chemical elements are very useful tools to understand everyday phenomena, and they "stand in place of" the complex motions of electrons around atomic nuclei, which are largely irrelevant for everyday applications.

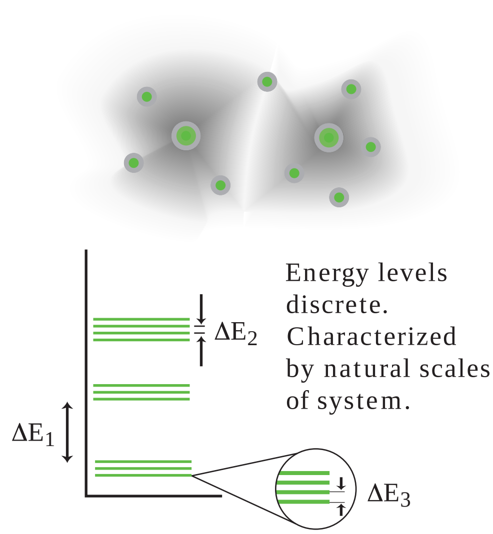
Chemistry and nuclear physics are both "effective theories" because quantum mechanics shields them from the complexity that lies beneath. This feature of quantum mechanics is largely responsible for the orderliness we perceive in the physical world, and it deserves more discussion. Consider a familiar substance such as water. At the simplest level, a chemist views pure water as a vast number of identical molecules, each composed of two hydrogen atoms bound to an oxygen atom. Deep within the atoms are nuclei: eight protons and eight neutrons for an oxygen nucleus, a single proton for hydrogen. Within the protons and neutrons are quarks and gluons. Within the quarks and gluons, who knows what? If classical mechanics described the world, each degree of freedom in this teeming microcosm could have an arbitrary amount of excitation energy. When disturbed, for example by a collision with another molecule, all the motions within the water molecule could be affected. In just this way, the Earth and everything on it would be thoroughly perturbed if our solar system collided with another.

Below: The "elementary" particles of the four schemes that have dominated modern science.

Scheme	Constituents	Date of Dominance	Domain of Applicability
Chemistry	92 Elements	Antiquity ~ 1900	$\gtrsim 10^{-8}$ cm
Nuclear	p,n,e,ν_e,γ	1900–1950	$\gtrsim 10^{-12}$ cm
Hadronic	$p,n,\Lambda,\Sigma,\pi,\rho,\ldots$	1950–1970	$\gtrsim 10^{-13}$ cm
Standard Model	Quarks, Leptons	1970–?	$\gtrsim 10^{-17}$ cm



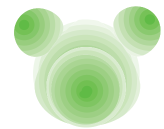
Energy Levels of a Classical System



Energy Levels of a Quantum System

Left: A schematic view of the energy levels of classical and quantum systems.

States of Water



	microwave meV	visible eV	soft γ–ray MeV	hard γ–ray GeV
Molecular	Active	Irrelevant	Irrelevant	Irrelevant
Atomic	Frozen	Active	Irrelevant	Irrelevant
Nuclear	Frozen	Frozen	Active	Irrelevant
Hadronic	Frozen	Frozen	Frozen	Active

The "quantum ladder" of water—the important degrees of freedom change with the scale on which it is probed, described here by the wavelength of light.

Quantum mechanics, on the other hand, does not allow arbitrary disruption. All excitations of the molecule are quantized, each with its own characteristic energy. Motions of the molecule as a whole—rotations and vibrations—have the lowest energies, in the 1–100 millielectron volt regime (1 meV = 10^{-3} eV). An electron volt, abbreviated eV, is the energy an electron gains falling through a potential of one volt and is a convenient unit of energy for fundamental processes. Excitation of the electrons in the hydrogen and oxygen atoms come next, with characteristic energies ranging from about 10^{-1} to 10^{3} eV. Nuclear excitations in oxygen require millions of electron volts (10^{6} eV = 1 MeV), and excitations of the quarks inside a proton require hundreds of MeV. Collisions between water molecules at room temperature transfer energies of order 10^{-2} eV, enough to excite rotations and perhaps vibrations, but too small to involve any of the deeper excitations except very rarely. We say that these variables—the electrons, the nuclei, the quarks—are "frozen." The energy levels of a classical and quantum system are compared in the bottom illustration on the previous page. They are inaccessible and unimportant. They are not static—the quarks inside the nuclei of water molecules are whizzing about at speeds approaching the speed of light—however their state of motion cannot be changed by everyday processes. Thus there is an excellent description of molecular rotations and vibrations that knows little about electrons and nothing about nuclear structure, quarks, or gluons. Light quanta make a particularly good probe of this "quantum ladder," as Victor Weisskopf called it. As summarized in the illustration above, as we shorten the wavelength of light we increase the energy of light quanta in direct proportion. As we move from microwaves to visible light to X rays to gamma rays we probe successively deeper layers of the structure of a water molecule. The appropriate constituent description depends on the scale of the probe. At one extreme, we cannot hope to describe the highest energy excitations of water without knowing about quarks and gluons; on the other hand, no one needs quarks and gluons to describe the way water is heated in a microwave oven.

PERHAPS THE MOST effective theory of all was the one invented by the nuclear physicists in the 1940s. It reigned for only a few years, before the discovery of myriad excited states of the proton and neutron led to its abandonment and eventual replacement with today's Standard Model of quarks and leptons. The nuclear standard model was based on three constituents: the proton (p); the neutron (n); and the electron (e). The neutrino (ν_e) plays a bit part in radioactive decays, and perhaps one should count the photon (γ), the quantum of the electromagnetic field. So the basic list is three, four, or five, roughly as short as Empedocles' and far more effective at explaining Nature. Most of nuclear physics and astrophysics and all of atomic, molecular, and condensed matter physics can be understood in terms of these few constituents. The nuclei of atoms are built up of protons and neutrons according to fairly simple empirical rules. Atoms, in turn, are composed of electrons held in orbit around nuclei by electromagnetism. All the different chemical elements from hydrogen (the lightest) to uranium (the heaviest naturally occurring) are just different organizations of electrons around nuclei with different electric charge. Even the radioactive processes that transmute one element into another are well described in the $pne\nu_e\gamma$ world.

The nuclear model of the world was soon replaced by another. Certain tell-tale signatures that emerged early in the 1950s made it clear that these "elementary" constituents were not so elementary after all. The same signatures of compositeness have repeated every time one set of constituents is replaced by another:

Excitations. If a particle is composite, when it is hit hard enough its component parts will be excited into a quasi-stable state, which later decays by emitting radiation. The hydrogen atom provides a classic example. When hydrogen atoms are heated so that they collide with one another violently, light of characteristic frequencies is emitted. As soon as it was understood that the light comes from the de-excitation of its inner workings, hydrogen's days as an elementary particle were over. Similarly, during the 1950s physicists discovered that when a proton or neutron is hit hard enough, excited states are formed and characteristic radiation (of light or other hadrons) is emitted. This suggest that protons and neutrons, like hydrogen, have inner workings capable of excitation and de-excitation. Of course, if only feeble energies are available, the internal structure cannot be excited, and it will not be possible to tell whether or not the particle is composite. So an experimenter needs a high-energy accelerator to probe compositeness by looking for excitations.

There is tantalizing evidence that new relationships await discovery.

Complex force laws. We have a deep prejudice that the forces between elementary particles should be simple, like Coulomb's law for the electrostatic force between point charges: $F_{12} = q_1q_2/r_{12}^2$. Because they derive from the complex motion of the electrons within the atom, forces between atoms are not simple. Nor, it turns out, are the forces between protons and neutrons. They depend on the relative orientation of the particles and their relative velocities; they are complicated functions of the distance between them. Nowadays the forces between the proton and neutron are summarized by pages of tables in the *Physical Review*. We now understand that they derive from the complex quark and gluon substructure within protons and neutrons.

The complicated features of force laws die away quickly with distance. So if an experimenter looks at a particle from far away or with low resolution, it is not possible to tell whether it is composite. A high-energy accelerator is needed to probe short distances and see the deviations from simple force laws that are telltale signs of compositeness.

Form factors. When two structureless particles scatter, the results are determined by the simple forces between them. If one of the particles has substructure, the scattering is modified. In general the probability of the scattered particle retaining its identity—this is known as "elastic scattering"—is reduced, because there is a chance that the particle will be excited or converted into something else. The factor by which the elastic scattering probability is diminished is known as a "form factor." Robert Hofstadter first discovered that the proton has a form factor in experiments performed at Stanford in the 1950s. This was incontrovertible evidence that the proton is composite.

If, however, one scatters lightly from a composite particle, nothing new is excited, and no form factor is observed. Once again, a high-energy accelerator is necessary to scatter hard enough to probe a particle's constituents.

Deep inelastic scattering. The best proof of compositeness is, of course, to detect directly the subconstituents out of which a particle is composed. Rutherford found the nucleus of the atom by scattering α particles from a gold foil and finding that some were scattered directly backwards, a result that would only be possible if the gold atoms contained a heavy concentration of mass—the nucleus—at their core. The famous SLAC experiments led by Jerome Friedman, Henry Kendall, and Richard Taylor found the analogous result for the proton: when they scattered electrons at large angles they found telltale evidence of pointlike quarks inside.

By the early 1970s mountains of evidence had forced the physics community to conclude that protons, neutrons, and their ilk are not fundamental, but are instead composed of quarks and gluons. During that decade Burton Richter and Sam Ting and their collaborators separately discovered the charm quark; Leon Lederman led the team that discovered the bottom quark; and Martin Perl's group discovered the third copy of the electron, the tau-lepton or tauon. The mediators of the weak force, the *W* and *Z* bosons, were discovered at CERN. The final ingredients in our present Standard Model are the top quark, recently discovered at Fermilab, and the Higgs boson, soon to be discovered at Fermilab or CERN. As these final blocks fall into place, we have a set of about 25 constituents from which all matter is built up.

THE STANDARD Model of particle physics is incredibly successful and predictive, but few believe it is the last word. There are too many particles—about 25—and too many parameters—also about 25 masses, interaction strengths, and orientation angles—for a fundamental theory.

	Excitation Spectrum	Form Factors	Complex Force Laws
92 Elements	Yes	Yes	Yes
p,n,e	Yes	Yes	Yes
Standard Model	No	No	No

Evidence for underlying structure in models of elementary constituents.

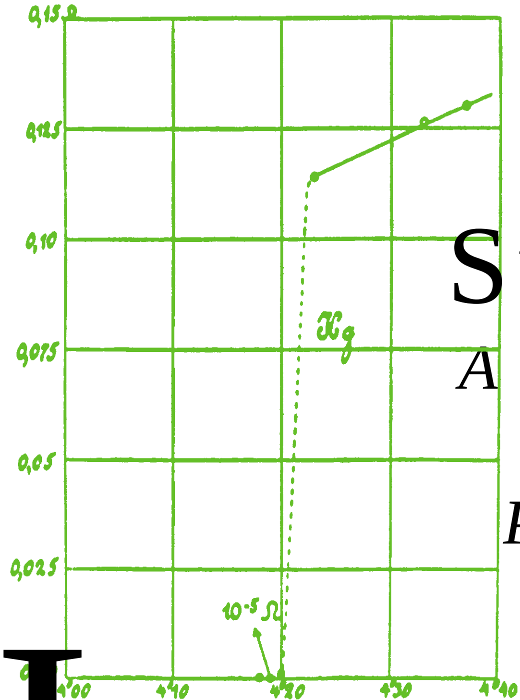
Particle physicists have spent the last quarter century looking for signs of what comes next. So far, they have come up empty—no signs of an excitation spectrum, complex force laws, or form factors have been seen in any experiment. The situation is summarized above. The Standard Model was discovered when physicists attempted to describe the world at distances smaller than the size of the proton, about 10^{-13} cm. Modern experiments have probed to distances about four orders of magnitude smaller, 10^{-17} cm, without evidence for substructure.

There is tantalizing evidence that new relationships await discovery. For example, the Standard Model does not require the electric charges of the quarks to be related to the electric charge of the electron. However, the sum of the electric charges of the three quarks that make up the proton has been measured by experiment to be the exact opposite of the charge on the electron to better than one part in 10^{20}. Such a relationship would follow naturally either if quarks and electrons were composed of common constituents or if they were different excitations states of some "ur" particle. Equally intriguing is that each quark and lepton seems to come in three versions with identical properties, differing only in mass. The three charged leptons, the electron, the muon and the tauon, are the best-known example, but the same holds for the up, charm, and top quarks, the down, strange, and bottom quarks, and the neutrinos associated with each lepton. The pattern looks very much like one of internal excitation—as if the muon and tauon are "excited electrons". However, extremely careful experiments have not been able to excite an electron into a muon or a tauon. The limits on these excitation processes are now extremely strong and pretty much rule out simple models in which the electron, muon, and tauon are "made up of" the same subconstituents in a straightforward way.

Building structures that relate the elementary particles of the Standard Model to one another is the business of modern particle theory. Supersymmetry (SUSY) combined with Grand Unification is perhaps the most promising approach. It removes some of the most troubling incongruities in the Standard Model. However, the cost is high—if SUSY is right, a huge number of new particles await discovery at the LHC or at the Next Linear Collider. The list of "elementary constituents" would more than double, as would the number of parameters necessary to describe their interactions. The situation would resemble the state of chemistry before the understanding of atoms, or of hadron physics before the discovery of quarks: a huge number of constituents, grouped into families, awaiting the next simplifying discovery of substructure.

One of the most striking properties of the Standard Model is the simplicity of the force laws. All the known forces between quarks and leptons are generalizations of Coulomb's Law. They all follow from symmetry considerations known as "gauge principles." Even gravity, which rests uneasily in the Standard Model, follows from the gauge principle that Einstein called "general covariance." The simplicity of the forces in the Standard Model has been mistaken for evidence that at last we have reached truly elementary constituents, and that there is no further substructure to be found. After all, the argument goes, "How could composite particles behave so simply?" Unfortunately, it turns out that it is quite natural for composite particles to mimic fundamental ones if we do not probe them deeply enough. The forces between atoms and nuclei look simple if one does not look too closely. Models with quite arbitrary interactions defined at very short distances produce the kind of forces we see in the Standard Model when viewed from far away. In a technical sense, the deviations from the forces that follow from the "gauge principle" are suppressed by factors like Λ/ℓ , where ℓ is the typical length scale probed by an experiment (ℓ scales like the inverse of the energy of the colliding particles), and Λ is the distance scale of the substructure. Holgar Nielsen and his collaborators have followed this thread of logic to an extreme, by exploring the extent to which an essentially random theory defined at the shortest distance scales will present itself to our eyes with gauge interactions like the Standard Model and gravity. These exercises show how much room there is for surprise when we probe the next level beyond the Standard Model.

We are poised rather uncomfortably upon a rung on Viki Weisskopf's Quantum Ladder. The world of quarks, leptons, and gauge interactions does a wonderful job of explaining the rungs below us: the nuclear world of $pne\nu_e\gamma$, the world of atoms, and chemistry. However, the internal consistency of the Standard Model and the propensity of quantum mechanics to shield us from what lies beyond, leave us without enough wisdom to guess what we will find on the next rung, or if, indeed, there is another rung to be found. Hints from the Standard Model suggest that new constituents await discovery with the next round of accelerator experiments. Hope from past examples motivates theorists to seek simplifications beyond this proliferation. Past experience cautions that we are a long way from the end of this exploration.



Superconductivity

A Macroscopic Quantum Phenomenon

by JOHN CLARKE

Drawing of Heike Kamerlingh Onnes made in 1922 by his nephew, Harm Kamerlingh Onnes. (Courtesy Kamerlingh Onnes Laboratory, Leiden University)

Upper left: Plot made by Kamerlingh Onnes of resistance (in ohms) versus temperature (in kelvin) for a sample of mercury. The sharp drop in resistance at about 4.2 K as the temperature was lowered marked the first observation of superconductivity.

IN THE NETHERLANDS IN 1911, about a decade after the discovery of quantum theory but more than a decade before the introduction of quantum mechanics, Heike Kamerlingh Onnes discovered superconductivity. This discovery came three years after he succeeded in liquefying helium, thus acquiring the refrigeration technique necessary to reach temperatures of a few degrees above absolute zero. The key feature of a superconductor is that it can carry an electrical current forever with no decay. The microscopic origin of superconductivity proved to be elusive, however, and it was not until 1957, after 30 years of quantum mechanics, that John Bardeen, Leon Cooper, and Robert Schrieffer elucidated their famous theory of superconductivity which held that the loss of electrical resistance was the result of electron "pairing." (See photograph on next page.)

In a normal metal, electrical currents are carried by electrons which are scattered, giving rise to resistance. Since electrons each carry a negative electric charge, they repel each other. In a superconductor, on the other hand, there is an attractive force between electrons of opposite momentum and opposite spin that overcomes this repulsion, enabling them to form pairs. These pairs are able to move through the material effectively without being scattered, and thus carry a supercurrent with no energy loss. Each pair can be described by a quantum mechanical "wave function." The remarkable property of the superconductor is that all electron pairs have

John Bardeen, Leon Cooper, and Robert Schrieffer (left to right) at the Nobel Prize ceremony in 1972. (Courtesy Emilio Segrè Visual Archives)

the same wave function, thus forming a macroscopic quantum state with a phase coherence extending throughout the material.

There are two types of superconductors. In 1957, Alexei Abrikosov showed that above a certain threshold magnetic field, type II superconductors admit field in the form of vortices. Each vortex contains one quantum of magnetic flux (product of magnetic field and area). Because supercurrents can flow around the vortices, these materials remain superconducting to vastly higher magnetic fields than their type I counterparts. Type II materials are the enabling technology for high-field magnets.

Shortly afterwards came a succession of events that heralded the age of superconducting electronics. In 1960, Ivar Giaever discovered the tunneling of electrons through an insulating barrier separating two thin superconducting films. If the insulator is sufficiently thin, electrons will "tunnel" through it. Building on this notion, in 1962 Brian Josephson predicted that electron pairs could tunnel through a barrier between two superconductors, giving the junction weak superconducting properties. Sure enough, this quantum mechanical phenomenon, called the "Josephson effect," was observed shortly afterwards at Bell Telephone Laboratories.

Between the two tunneling discoveries, in 1961, there occurred another discovery that was to have profound implications: flux quantization. Because supercurrents are lossless, they can flow indefinitely around a superconducting loop, thereby maintaining a permanent magnetic field. This is the principle of the high-field magnet. However, the magnetic flux threading the ring cannot take arbitrary values, but instead is quantized in units of the flux quantum. The superconductor consequently mimics familiar quantum effects in atoms but does so on a macroscopic scale.

For most of the century, superconductivity was a phenomenon of liquid helium temperatures; a compound of niobium and germanium had the highest transition temperature, about 23 K. In 1986, however, Alex Mueller and Georg Bednorz staggered the physics world with their announcement of superconductivity at 30 K in a layered oxide of the elements lanthanum, calcium, copper, and oxygen. Their amazing breakthrough unleashed a worldwide race to discover materials with higher critical temperatures. Shortly afterwards, the discovery of superconductivity in a compound of yttrium, barium, copper, and oxygen at 90 K ushered in the new age of superconductors for which liquid nitrogen, boiling at 77 K, could be used as the cryogen. Today the highest transition temperature, in a mercury-based oxide, is about 133 K.

Why do these new materials have such high transition temperatures? Amazingly, some 13 years after their discovery, nobody knows! While it is clear that hole pairs carry the supercurrent, it is unclear what glues them together. The nature of the pairing mechanism in high-temperature superconductors remains one of the great physics challenges of the new millennium.

LARGE-SCALE APPLICATIONS

Copper-clad wire made from an alloy of niobium and titanium is the conductor of choice for magnetic fields up to 10 tesla. Magnets made of this wire are widely used in experiments ranging from high-field nuclear magnetic resonance to the study of how electrons behave in the presence of extremely high magnetic fields. The largest scale applications of superconducting wire, however, are in magnets for particle accelerators and magnetic resonance imaging (MRI). Other prototype applications include cables for power transmission, large inductors for energy storage, power generators and electric motors, magnetically levitated trains, and bearings for energy-storing flywheels. Higher magnetic fields can be achieved with other niobium alloys involving tin or aluminum, but these materials are brittle and require special handling. Much progress has been made with multifilamentary wires consisting of the high temperature superconductor bismuth-strontium-calcium-copper-oxide sheathed in silver. Such wire is now available in lengths of several hundred meters and has been used in demonstrations such as electric motors and power transmission. At 4.2 K this wire remains superconducting to higher magnetic fields than the niobium alloys, so that it can be used as an insert coil to boost the magnetic field produced by low-temperature magnets.

The world's most powerful particle accelerators rely on magnets wound with superconducting cables. This cable contains 20–40 niobium-titanium wires in parallel, each containing 5,000–10,000 filaments capable of carrying 10,000 amperes (see Judy Jackson's article "Down to the Wire" in the Spring 1993 issue).

The first superconducting accelerator to be built was the Tevatron at Fermi National Accelerator Laboratory in 1984. This 1 TeV machine

Tevatron superconducting dipole magnets and correction assembly in Fermilab's Main Ring tunnel. (Courtesy Fermi National Accelerator Laboratory)

incorporates 800 superconducting magnets. Other superconducting accelerators include HERA at the Deutsches Elektronen Synchrotron in Germany, the Relativistic Heavy Ion Collider nearing completion at Brookhaven National Laboratory in New York, and the Large Hadron Collider (LHC) which is being built in the tunnel of the existing Large Electron Positron ring at CERN in Switzerland. The LHC, scheduled for completion in 2005, is designed for 14 TeV collision energy and, with quadrupole and corrector magnets, will involve more than 8,000 superconducting magnets. The dipole field is 8.4 tesla. The ill-fated Superconducting Super Collider was designed for 40 TeV and was to have involved 4,000 superconducting dipole magnets. At the other end of the size and energy scale is Helios 1, a 0.7 GeV synchrotron X-ray source for lithography operating at IBM. From these examples, it becomes clear that the demanding requirements of accelerators have been a major driving force behind the development of superconducting magnets. Their crucial advantage is that they dissipate very little power compared with conventional magnets.

Millions of people around the world have been surrounded by a superconducting magnet while having a magnetic resonance image (MRI) taken of themselves. Thousands of MRI machines are in everyday use, each containing tens of kilometers of superconducting wire wound into a persistent-current solenoid. The magnet is cooled either by liquid helium or by a cryocooler. Once the current has been stored in the superconducting coil, the magnetic field is very stable, decaying by as little as a part per million in a year.

Conventional MRI relies on the fact that protons possess spin and thus a magnetic moment. In the MRI machine, a radiofrequency pulse of magnetic field induces protons in the patient to precess about the direction of the static magnetic field supplied by the superconduting magnet. For the workhorse machines with a field of 1.5 T, the precessional frequency, which is precisely proportional to the field, is about 64 MHz. These precessing magnetic moments induce a radiofrequency voltage in a receiver coil that is amplified and stored for subsequent analysis. If the magnetic field were uniform, all the protons would precess at the same frequency. The key to obtaining an image is the use of magnetic field gradients to define a "voxel," a volume typically 3 mm across. One distinguishes structure by virtue of the fact that,

A 1.5 tesla MRI scanner at Stanford University for a functional neuroimaging study. The person in the foreground is adjusting a video projector used to present visual stimuli to the subject in the magnet. (Courtesy Anne Marie Sawyer-Glover, Lucas Center, Stanford University) for example, fat and muscle and grey and white matter produce different signal strengths.

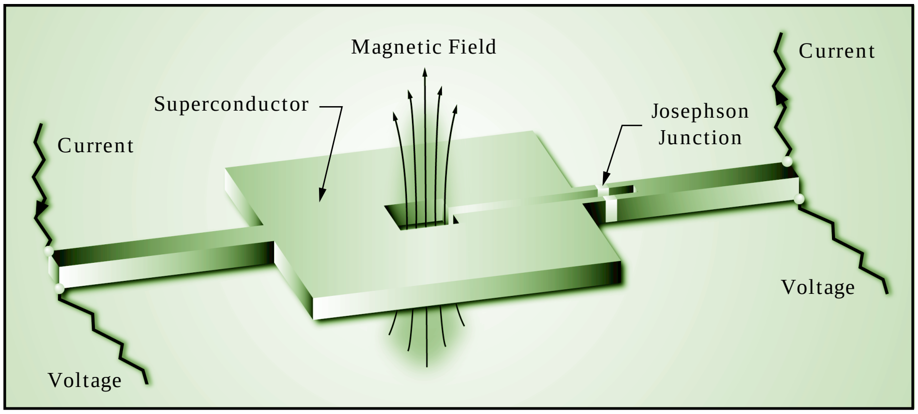
MRI has become a clinical tool of great importance and is used in a wide variety of modes. The development of functional magnetic resonant imaging enables one to locate some sites in the brain that are involved in body function or thought. During brain activity, there is a rapid, momentary increase in blood flow to a specific site, thereby increasing the local oxygen concentration. In turn, the presence of the oxygen modifies the local MRI signal relative to that of the surrounding tissue, enabling one to pinpoint the neural activity. Applications of this technique include mapping the brain and pre-operative surgical planning.

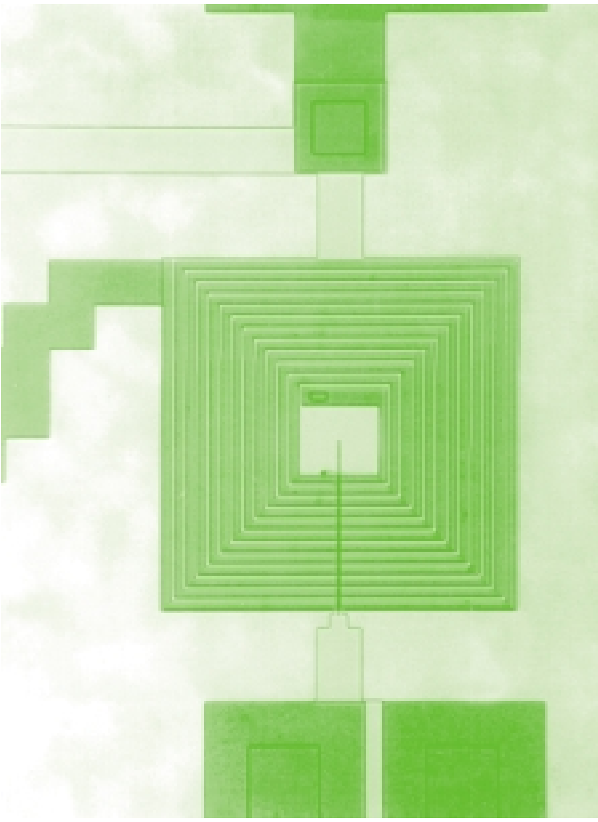
SMALL-SCALE APPLICATIONS

At the lower end of the size scale (less than a millimeter) are extremely sensitive devices used to measure magnetic fields. Called "SQUIDS" for superconducting quantum interference devices, they are the most sensitive type of detector known to science, and can turn a change in a magnetic field, something very hard to measure, into a change in voltage, something easy to measure. The dc SQUID consists of two junctions connected in parallel to form a superconducting loop. In the presence of an appropriate current, a voltage is developed across the junctions. If one changes the magnetic field threading the loop, this voltage oscillates back and forth with a period of one flux quantum. One detects a change in magnetic field by measuring the resulting change in voltage across the SQUID using conventional electronics. In essence, the SQUID is a flux-to-voltage transducer.

Squids are fabricated from thin films using photolithographic techniques to pattern them on a silicon wafer. In the usual design, they consist of a square washer of niobium containing a slit on either side of which is a tunnel junction. The upper electrodes of the junctions are connected to close the loop. A spiral niobium coil with typically 50 turns is deposited over the top of the washer, separated from it by an insulating layer. A current passed through the coil efficiently couples flux to the SQUID. A typical SQUID can detect one part per million of a flux quantum, and it is this remarkable sensitivity that makes possible a host of applications.

Generally, SQUIDs are coupled to auxiliary components, such as a superconducting loop connected to the input terminals of the coil to form a "flux transformer." When we apply a magnetic field to this loop, flux quantization induces a supercurrent in the transformer and hence a flux in the SQUID. The flux transformer functions as a sort of "hearing aid," enabling one to detect a



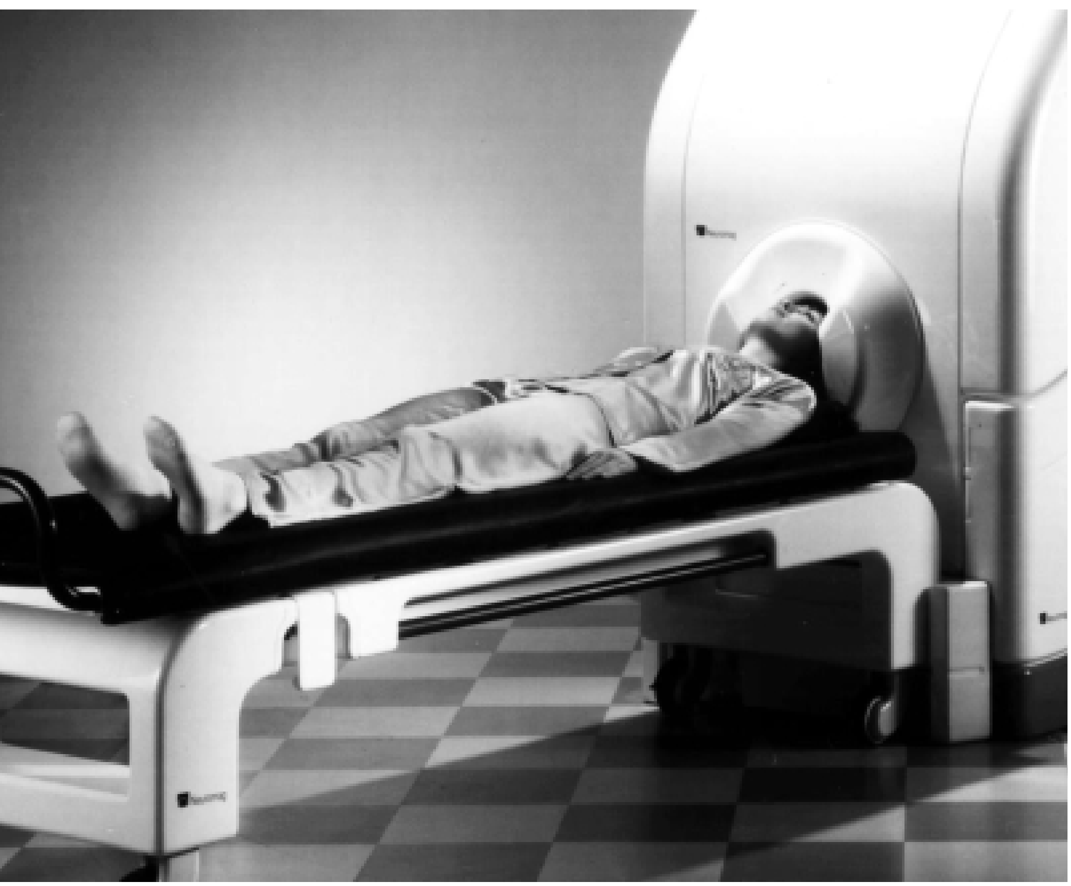


Top: A dc SQUID configuration showing two Josephson junctions connected in parallel. Bottom: A high transition temperature SQUID. The yttrium-barium-copper-oxide square washer is 0.5 mm across.

magnetic field as much as eleven orders of magnitude below that of the magnetic field of the earth. If, instead, we connect a resistance in series with the SQUID coil, we create a voltmeter that readily achieves a voltage noise six orders of magnitude below that of semiconductor amplifiers.

It is likely that most SQUIDs ever made are used for studies of the human brain. Commercially available systems contain as many as 306 sensors arranged in a helmet containing liquid helium that fits around the back, top, and sides of the patient's skull. This completely non-invasive technique enables one to detect the tiny magnetic fields produced by thousands of neurons firing in concert. Although the fields outside the head are quite large by SQUID standards, they are minuscule compared with environmental magnetic noise—cars, elevators, television stations. To eliminate these noise sources, the patient is usually enclosed in a magnetically-shielded room. In addition, the flux transformers are generally configured as spatial gradiometers that discriminate against distant noise sources in favor of nearby signal sources. Computer processing of the signals from the array of SQUIDs enables one to locate the source to within 2–3 mm.

System containing 306 SQUIDs for the detection of signals from the human brain. The liquid helium that cools the devices needs to be replenished only once a week. The system can be rotated so as to examine seated patients. The magnetic images are displayed on a workstation (not shown). (Courtesy 4D-Neuroimaging)



There are two broad classes of signal: stimulated, the brain's response to an external stimulus; and spontaneous, self-generated by the brain. An example of the first is presurgical screening of brain tumors. By applying stimuli, one can map out the brain function in the vicinity of the tumor, thereby enabling the surgeon to choose the least damaging path to remove it. An example of spontaneous signals is their use to identify the location of epileptic foci. The fast temporal response of the SQUID, a few milliseconds, enables one to demonstrate that some patients have two foci, one of which stimulates the other. By locating the epileptic focus non-invasively before surgery, one can make an informed decision about the type of treatment. Research is also under way on other disorders, including Alzheimer's and Parkinson's diseases, and recovery from stroke.

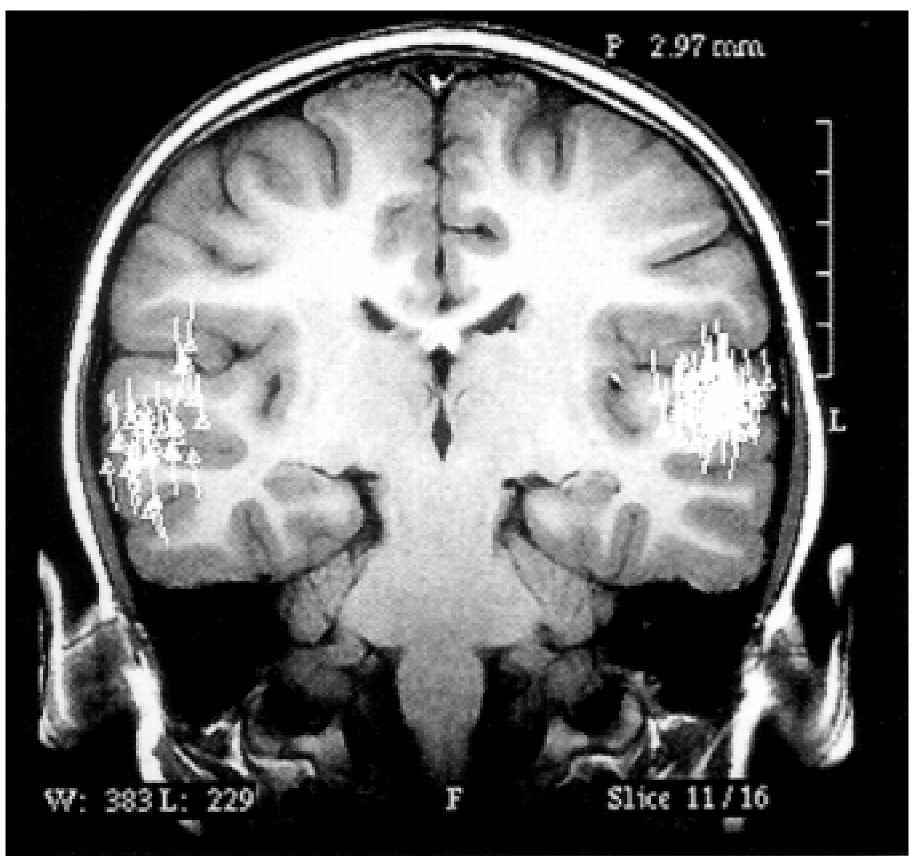
There are many other applications of low-temperature SQUIDs, ranging from the ultra-sensitive detection of nuclear magnetic resonance to searches for magnetic monopoles and studies of the reversal of the Earth's magnetic field in ancient times. A recent example of the SQUID's versatility is the proposal to use it as a high-frequency amplifier in an upgraded axion detector at Lawrence Livermore National Laboratory. The axion is a candidate particle for the cold dark matter that constitutes a large fraction of the mass of the Universe (see article by Leslie Rosenberg and Karl van Bibber in the Fall 1997 *Beam Line*, Vol. 27, No. 3).

With the advent of high-temperature superconductivity, many groups around the world chose the SQUID to develop their thin-film technology. Yttrium-barium-copper-oxygen dc SQUIDs operating in liquid nitrogen achieve a magnetic field sensitivity within a factor of 3–5 of their liquid-helium cooled cousins. High-temperature SQUIDs find novel applications in which the potential economy and convenience of cooling with liquid nitrogen or a cryocooler are strong incentives. Much effort has been expended to develop them for magnetocardiography (MCG) in an unshielded environment. The magnetic signal from the heart is easily detected by a SQUID in a shielded enclosure. However, to reduce the system cost and to make MCG more broadly available, it is essential to eliminate the shielded room. This challenge can be met by taking spatial derivatives, often with a combination of hardware and software, to reduce external interference. What advantages does MCG offer over conventional electrocardiography? One potentially important application is the detection of ischemia (localized tissue anemia); another is to locate the site of an arrhythmia. Although extensive clinical trials would be required to demonstrate its efficacy, MCG is entirely non-invasive and may be cheaper and faster than current techniques.

Ground-based and airborne high temperature SQUIDs have been used successfully in geophysical surveying trials. In Germany, high temperature SQUIDs are used to examine commercial aircraft wheels for possible flaws produced by the stress and heat generated at landing.

The advantage of the higher operating temperature of high temperature SQUIDs is exemplified

Localization of sources of magnetic spikes in a five-year-old patient with Landau-Kleffner syndrome (LKS). The sources, shown as arrows at left and right, are superimposed on a magnetic resonance image of the brain. LKS is caused by epileptic activity in regions of the brain responsible for understanding language and results in a loss of language capabilities in otherwise normal children. (Courtesy 4D-Neuroimaging and Frank Morrell, M.D., Rush-Presbyterian-St. Luke's Medical Center)



in “SQUID microscopes,” in which the device, mounted in vacuum just below a thin window, can be brought very close to samples at room temperature and pressure. Such microscopes are used to detect flaws in semiconductor chips and to monitor the gyrations of magnetotactic bacteria, which contain a tiny magnet for navigational purposes.

Although SQUIDs dominate the small-scale arena, other devices are important. Most national standards laboratories around the world use the ac Josephson effect to maintain the standard volt. Superconducting detectors are revolutionizing submillimeter and far infrared astronomy. Mixers involving a low temperature superconductor-insulator-superconductor (SIS) tunnel junction provide unrivaled sensitivity to narrow-band signals, for example, those produced by rotational transitions of molecules in interstellar space. Roughly 100 SIS mixers are operational on ground-based radio telescopes, and a radio-telescope array planned for Chile will require about 1000 such mixers. When one requires broadband detectors—for example, for the detection of the cosmic background radiation—the low temperature superconducting-transition-edge bolometer is the device of choice in the submillimeter range. The bolometer absorbs incident radiation, and the resulting rise in its temperature is detected by the change in resistance of a superconductor at its transition; this change is read out by a SQUID. Arrays of 1,000 or even 10,000 such bolometers are contemplated for satellite-based telescopes for rapid mapping of the cosmos—not only in the far infrared but also for X-ray astronomy. Superconducting detectors are poised to play a crucial role in radio and X-ray astronomy.

A rapidly growing number of cellular base stations use multipole high temperature filters on their receivers, yielding sharper bandwidth definition and lower noise than conventional filters. This technology enables the provider to pack more channels into a given frequency allocation in urban environments and to extend the distance between rural base stations.

THE NEXT MILLENNIUM

The major fundamental questions are “Why are high temperature superconductors superconducting?” and “Can we achieve still higher temperature superconductors?” On the applications front, the development of a high temperature wire that can be manufactured cost effectively in sufficient lengths could revolutionize power generation, transmission, and utilization. On the small-scale end, superconducting detector arrays on satellites may yield new insights into the origins of our Universe. High temperature filters will provide rapid internet access from our cell phones. The combination of SQUID arrays and MRI will revolutionize our understanding of brain function. And perhaps a SQUID will even catch an axion.

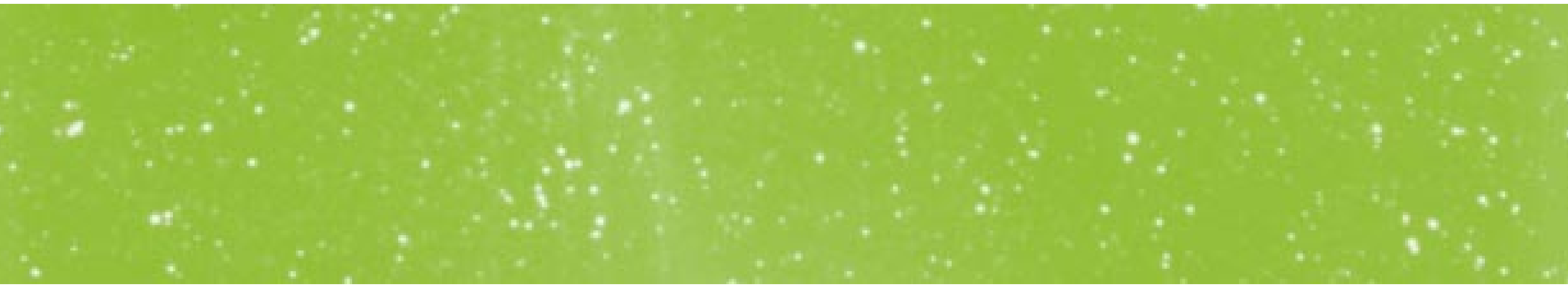
by VIRGINIA TRIMBLE

The Ratios of Small Whole Numbers: Misadventures in Astronomical Quantization

This is also Part III of "Astrophysics Faces the Millennium," but there are limits to the number of subtitles that can dance on the head of an editor.

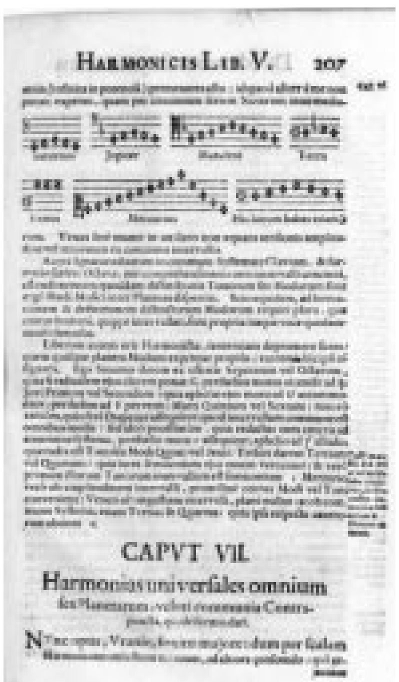
GOD MADE THE INTEGERS; all else is the work of Man. So said Kronecker of the delta. And indeed you can do many things with the integers if your tastes run in that direction. A uniform density stretched string or a pipe of uniform bore will produce a series of tones that sound pleasant together if you stop the string or pipe into lengths that are the ratios of small whole numbers. Some nice geometrical figures, like the 3-4-5 right triangle, can also be made this way. Such things were known to Pythagoras in the late sixth century BCE and his followers, the Pythagoreans. They extended the concept to the heavens, associating particular notes with the orbits of the planets, which therefore sang a harmony or music of the spheres, finally transcribed in modern times by Gustav Holtz.

A fondness for small whole numbers and structures made of them, like the regular or Platonic solids, persisted for centuries. It was, in its way, like our fondness for billions and billions, a fashion. George Bernard Shaw claimed early in the twentieth century that it was no more rational for his contemporaries to think they were sick because of an invasion by millions of germs than for their ancestors to have attributed the problem to an invasion by seven devils. Most of us would say that the germ theory of disease today has a firmer epistomological basis than the seven devils theory. But the insight that there are fashions in numbers and mathematics, as much as fashions in art and government, I think stands.



KEPLER'S LAWS AND LAURELS

Some of the heroes of early modern astronomy remained part of the seven devils school of natural philosophy. We laud Johannes Kepler (1571–1630) for his three laws of planetary motion that were later shown to follow directly from a Newtonian, inverse-square law of gravity, but he had tried many combinations of small whole numbers before showing that the orbit periods and orbit sizes of the planets were connected by $P^2 = a^3$. And the same 1619 work, Harmony of the Worlds, that enunciated this relation also showed the notes sung by the planets, in a notation that I do not entirely understand. Venus hummed a single high pitch, and Mercury ran up a glissando and down an arpeggio, while Earth moaned mi(seria), fa(mes), mi(seria). The range of notes in each melody depended on the range of speeds of the planet in its orbit, which Kepler, with his equal areas law, had also correctly described.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CAPVT VII.

Harmonias universales omnium

The music of the spheres according to Kepler. Saturn (upper left) is scored on the familiar bass clef, with F on the second line from the top, and Venus (beneath Saturn) on a treble clef with G on the second line from the bottom. The others are F, G, and C clefs with the key notes on other lines, not now generally in use. (Copyright © 1994, UK ATC, The Royal Observatory, Edinburgh.)

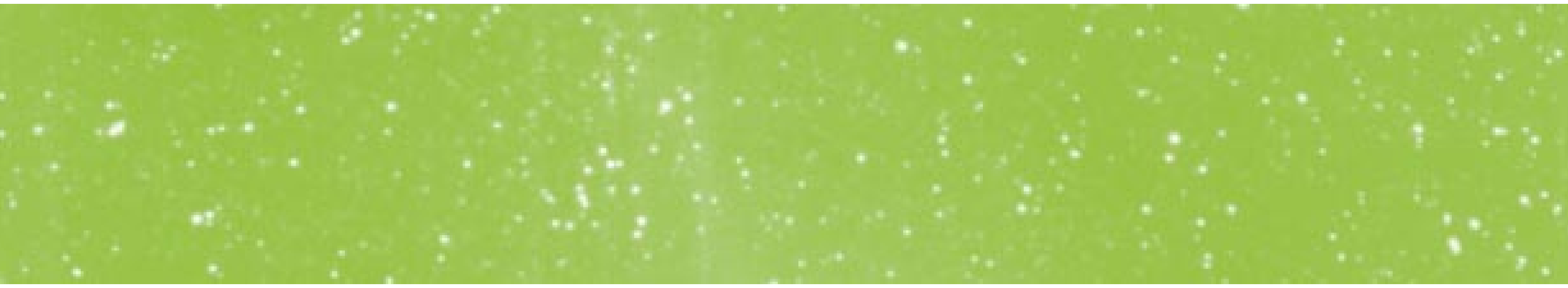
Kepler's planets were, however, six, though Copernicus and Tycho had clung to seven, by counting the moon, even as they rearranged Sun and Earth. Why six planets carried on six spheres? Why, because there are precisely five regular solids to separate the spheres: cube, pyramid, octahedron, dodecahedron, and icosahedron. With tight packing of sequential spheres and solids in the right order, Kepler could approximately reproduce the relative orbit sizes (semi-major axes) required to move the planets to the positions on the sky where we see them. Though this scheme appears in his 1596 Cosmographic Mystery and so belongs to Kepler's geometric youth, he does not appear to have abandoned it in his algebraic maturity.

EXCESSIVELY UNIVERSAL GRAVITATION

Newton (1643–1727) was born the year after Galileo died and died only two years before James Bradley recognized aberration of starlight, thereby demonstrating unambiguously that the Earth goes around the Sun and that light travels about 10^4 times as fast as the Earth's orbit speed (NOT a ratio of small whole numbers!) But the SWN ideal persisted many places. Galileo had found four moons orbiting Jupiter (which Kepler himself noted also followed a $P^2 = a^3$ pattern around their central body), and the Earth had one. Mars must then naturally have two. So said Jonathan Swift in 1726, attributing the discovery to Laputian* astronomers, though it was not actually made until 1877 by Asaph Hall of the U.S. Naval Observatory.

Attempts to force-fit Newtonian gravity to the entire solar system have led to a couple of ghost planets, beginning with Vulcan, whose job was to accelerate the rotation of the orbit of Mercury ("advance of the perihelion") until Einstein and General Relativity were ready to take it on. Planet X, out beyond Pluto, where it might influence the orbits of comets, and Nemesis, still further out and prone to sending comets inward to impact the Earth every 20 million years or so, are more recent examples. They have not been observed, and, according to dynamicist Peter Vandervoort of the University of Chicago, the Nemesis orbit is dynamically very interesting; it just happens not to be occupied.

**It is, I suspect, nothing more than bad diction that leads to the frequent false attribution of the discovery to Lilliputian astronomers, when their culture must surely have specialized in microscopy.*



THE GREGORY-WOLFF-BONNET LAW

Meanwhile, the small whole numbers folk were looking again at the known planetary orbits and trying to describe their relative sizes. Proportional to 4, 7, 10, 15, 52, and 95, said David Gregory of Oxford in 1702. The numbers were published again, in Germany, by Christian Wolff and picked up in 1766 by a chap producing a German translation of a French volume on natural history by Charles Bonnet. The translator, whose name was Johann Titius (of Wittenberg) added the set of numbers to Bonnet's text, improving them to 4, 7, 10, 16, 52, and 100, that is 4+0, 4+3, 4+6, 4+12, 4+48, and 4+96, or 4+ (3×0,1,2,4,16,32). A second, 1712, edition of the translation reached Johann Elert Bode, who also liked the series of numbers, published them yet again in an introduction to astronomy, and so gave us the standard name Bode's Law, not, as you will have remarked, either a law or invented by Bode.

Bode, at least, expected there to be a planet at 4 + 3×8 units (2.8 AU), in the region that Newton thought the creator had left empty to protect the inner solar system from disruption by the large masses of Jupiter and Saturn. Closely related seventeenth century explanations of the large separation from Mars to Jupiter included plundering of the region by Jupiter and Saturn and collisional disruptions. Don't forget these completely, since we'll need them again. Great, however, was the rejoicing in the small whole numbers camp when William Herschel spotted Uranus in 1781 in an orbit not far from 4 + 192 units from the sun.

Among the most impressed was Baron Franz Xaver von Zach of Gotha (notice the extent to which this sort of numerical/positional astronomy seems to have been a German enterprise). After a few years of hunting the skies where an a = 28 unit planet might live, he and few colleagues decided to enlist a bunch of European colleagues as "celestial police," each to patrol a fixed part of the sky in search of the missing planet. Hegel, of the same generation and culture, on the other hand, objected to potential additional planets, on the ground that Uranus had brought us back up to seven, equal to the number of holes in the average human head, and so the correct number.*

Even as von Zach was organizing things, Italian astronomer Giuseppe Piazzi, working independently on a star catalog, found, on New Year's Day 1801, a new moving object that he at first took to be a comet before losing it behind the sun in February. Some high powered mathematics by the young Gauss (whom astronomers think of as the inventor of the least squares method in this context) provided a good enough orbit for Zach to recover the wanderer at the end of the year. Sure enough, it had a roughly circular orbit of about the size that had been Boded. But it was smaller than our own moon and, by 1807, had acquired three stablemates. These (Ceres, Juno, Pallas, and Vesta) were, of course, the first four of many thousands of asteroids, whose total mass is nevertheless still not enough to make a decent moon. I do not know whether Piazzi made his discovery in the sky sector that von Zach had assigned to him or whether, if not, the person who was supposed to get that sector was resentful, though the latter seems likely.

Neptune and Pluto entered the planetary inventory with orbits quite different and smaller than the next two terms in the Titius-Bode sequence. Strong expectation that they should fall at the sequence positions probably retarded the searches for them (which were based on irregularities in the motion of Uranus).

In recent years, the orbits of triplets of planets around one pulsar and one normal star (Ups And) have also been claimed as following something like a Gregory-Wolff-Titius sequence. Notice however that it takes two orbits to define the sequence, even in completely arbitrary units.

What is the status of Bode's Law today? The table on the next page shows the actual orbit semi-major axes and the fitted number sequence. All agree to about five

It is left as an exercise for the reader to formulate an appropriate snide remark about Hegel having thus physiologically anticipated the discovery of Neptune, which he did not in fact live to see.

Planetary Orbit Sizes

Astronomical Object	Mean Orbit Size in Titius-Bode sequence	Actual Semi-Major Axis in AU×10
Mercury	4	3.87
Venus	7	7.32
Earth	10	10.0 (definition)
Mars	16	15.24
Asteroid belt (mean)	28	26.8
Jupiter	52	52.03
Saturn	100	95.39.
Uranus	196	191.9
Neptune	388	301
Pluto	722	395

percent until you reach Neptune. But current theory comes much closer to what Newton and his contemporaries said than to orbit quantization. The process of formation of the planets and subsequent stability of their orbits are possible only if the planets further from the sun, where the gravitational effect of the sun is progressively weaker, are also further from each other.

BI- AND MULTI-MODALITIES

The minimum requirement for quantization is two entities with different values of something. With three you get eggroll, and twentieth century astronomy has seen a great many divisions of its sources into two discrete classes. Examples include galactic stars into populations I and II; star formation processes into those making high and low mass stars; binary systems into pairs with components of nearly equal vs. very unequal masses; stellar velocities into two streams; and supernovae into types I and II (occurring in populations II and I respectively).

None of these has achieved the status of true crankiness. Rather, most have eventually either smoothed out into some kind of continuum, from which early investigations had snatched two widely separated subsets (stellar populations, for instance), or *n*-furcated into "many," each with honorably different underlying physics (including supernova types). A few, like the distinction between novae and supernovae, turned out to be wildly different sorts of things, initially perceived as similar classes because of some major misconception (that their distances were similar, in the nova-supernova case).

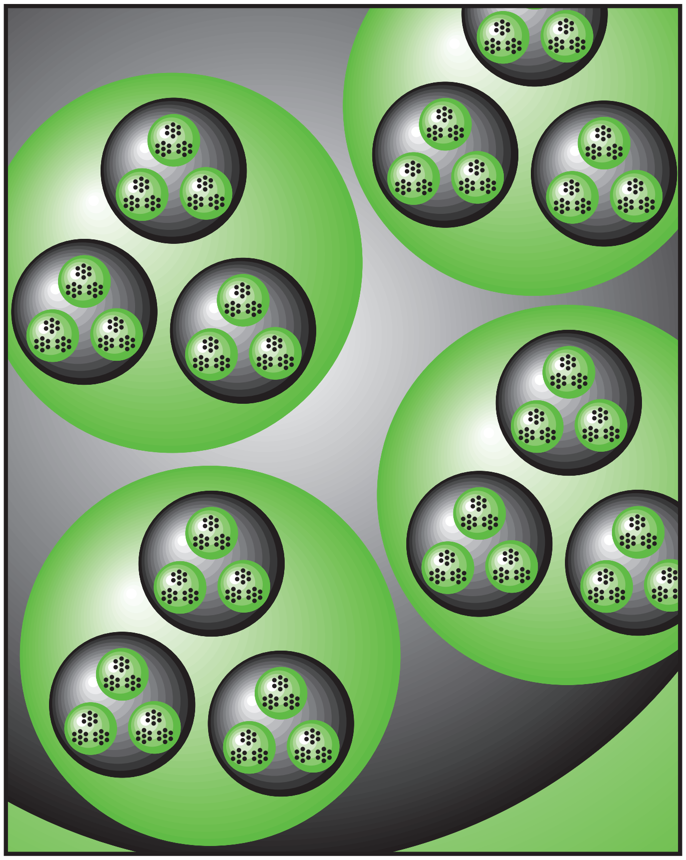
Thus to explore the extremities of weirdness in astronomical quantization, we must jump all the way from the solar system to the wilder reaches of quasars and cosmology. Here will we find fractals, universes with periodic boundary conditions, non-cosmological (and indeed non-Doppler and non-gravitational redshifts), and galaxies that are permitted to rotate only at certain discrete speeds.

FRACTAL, TOPOLOGICALLY-COMPLEX, AND PERIODIC UNIVERSES

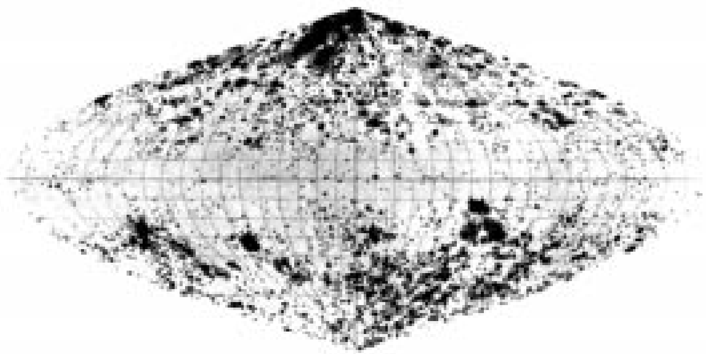
In the cosmological context, fractal structure would appear as a clustering heirarchy. That is, the larger the scale on which you looked at the distribution of galaxies (etc.), the larger the structures you would find. Many pre-Einsteinian pictures of the Universe were like this, including ones conceived by Thomas Wright of Durham, Immanuel Kant, and Johann Lambert (all eighteenth century). Since we have global solutions for the equations of GR only for the case of homogeneity and isotropy on average, it is not entirely clear what a general relativistic fractal universe ought to look like.

But it probably doesn't matter. Observations of distances and locations of galaxies currently tell us that there are clusters and superclusters of galaxies (often sheet-like or filamentary) with voids between, having sizes up to 100–200 million parsecs. This is less than 10 percent of the distance to galaxies with large redshifts. No honest survey of galaxy positions and distances has found structure larger than this, though a couple of groups continue to reanalyze other people's data and report fractal or heirarchical structure out to billions of

parsecs. A naive plot of galaxies on the sky indeed appears to have a sort of quadrupole, but the cause is dust in our own galaxy absorbing the light coming from galaxies in the direction of the galactic plane, not structure on the scale of the whole observable Universe.



A non-artist's impression of a hierarchical or fractal universe in which observations on ever-increasing length scales reveal ever-larger structure. In this realization, the first order clusters each contain seven objects, the next two orders have three each, and the fourth order systems (where we run off the edge of the illustration) at last four. Immanuel Kant and others in the eighteenth century proposed this sort of structure, but modern observations indicate that there is no further clustering for sizes larger than about 150 million parsecs. (Adapted from Edward R. Harrison's Cosmology, The Science of the Universe, *Cambridge University Press, second edition, 2000. Reprinted with the permission of Cambridge University Press)*



A plot of the distribution of nearby galaxies on the sky, dating from before the confirmation that other galaxies exist and that the Universe is expanding. Most of the small clumps are real clusters, but the concentration toward the poles and dearth at the equator (in galactic coordinates) result from absorption of light by dust in the plane of our own Milky Way. [From C. V. L. Charlier, Arkiv. for Mat. Astron., Fys *16, 1 (1922)]*

Coming at the problem from the other side, the things that we observe to be very isotropic on the sky, including bright radio sources, the X-ray background, gamma ray bursts, and, most notoriously, the cosmic microwave radiation background have been used by Jim Peebles of Princeton to show that either (a) the large scale fractal dimension $d = 3$ to a part in a thousand (that is, in effect, homogeneity over the distances to the X-ray and radio sources), or (b) we live very close indeed to the center of an inhomogeneous but spherically symmetric (isotropic) universe.

Several of the early solvers of the Einstein equations, including Georges Lemaitre, Alexander Friedmann, and Willem de Sitter, considered at least briefly the idea of a universe with topology more complex than the minimum needed to hold it together.

Connecting little, remote bits of universe together with wormholes, Einstein-Rosen bridges, or whatever is not a good strategy, at least for the time and space scales over which we observe the cosmic microwave background. If you peered through such a connection in one direction and not in the patch of sky next to it, the

photons from the two directions would have different redshlfts, that is different temperatures. The largest temperature fluctuations we see are parts in 10^5, so the light travel time through the wormhole must not differ from the travel time without it by more than that fraction of the age of the Universe, another conclusion expressed clearly by Peebles.

A periodic universe, in which all the photons go around many times, is harder to rule out. Indeed it has been invoked a number of times. The first camp includes people who have thought they had seen the same object or structure by looking at different directions in the sky and those who have pointed out that we do not see such duplicate structures, though we might well have, and, therefore, that the cell size of periodic universe must be larger than the distance light travels in a Hubble time. The second camp includes people who want to use periodic boundary conditions to explain the cosmic microwave background (it's our own galaxy seen simultaneously around the Universe in all directions), high energy cosmic rays (photons which have been around many times, gaining energy as they go), or the centers of quasars (bright because they illuminate themselves).

Descending a bit from that last peak of terminal weirdness, we note that a periodic universe, with cell size much smaller than the distance light goes in 10–20 billion years, automatically guarantees that the radio and X-ray sources will be seen quite isotropically on the sky. It also has no particle horizon, if that is the sort of thing that bothers you.

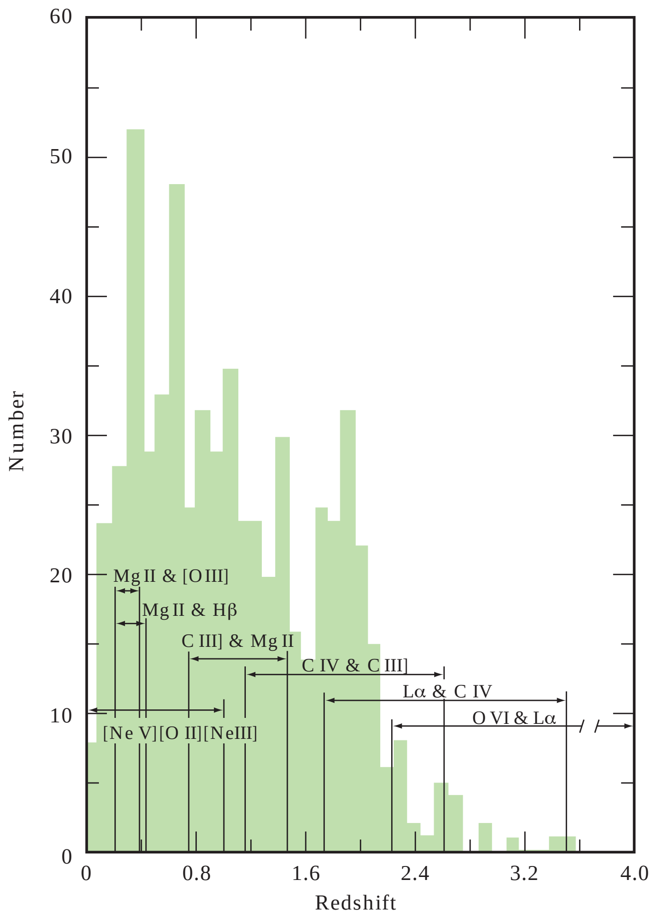
Each year, the astronomical literature includes a few cosmological ideas about which one is tempted to say (with Pauli?) that it isn't even wrong. A couple of my favorites from the 1990s are a universe with octehedral geometry (the advertised cause is magnetic fields) and one with a metric that oscillates at a period of 160 minutes (accounting for fluctuations in the light of the Sun and certain variable stars).

QUANTIZED VELOCITIES AND REDSHIFTS

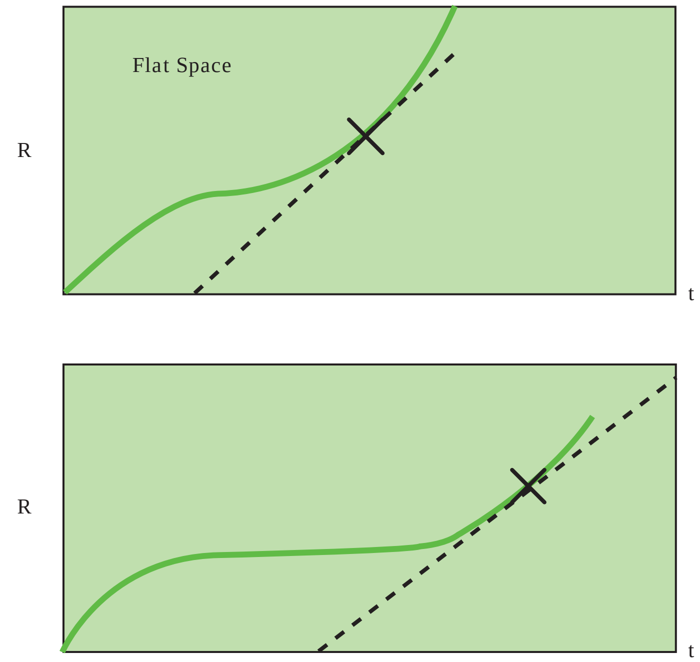
The ideas along these lines that still bounce around the literature all seem to date from after the discovery of quasars, though the quantization intervals are as small as 6 km/sec. The topic is closely coupled (a) with redshifts whose origins are not due to the expansion of the Universe, strong gravitation, or relative motion, but to some new physics and (b) with alternatives to standard hot Big Bang comology, especially steady state and its more recent offspring. The number of people actively working on and supporting these ideas does not seem to be more than a few dozen (of a world wide astronomical community of more than 10,000), and most of the papers come from an even smaller group. This is not, of course, equivalent to the ideas being wrong. But they have been out in the scholarly marketplace for many years without attracting vast numbers of buyers.

The underlying physics that might be responsible for new kinds of wavelength shifts and/or quantized wavelength shifts have not been worked out in anything like the mathematical detail of the Standard Model and processes. One suggestion is that new matter is added to the Universe in such a way that the particles initially have zero rest mass and gradually grow to the values we see. This will certainly result in longer wavelengths from younger matter, since the expression for the Bohr energy levels has the electron rest mass upstairs. Quantized or preferred redshifts then require some additional assumption about matter not entering the Universe at a constant rate.

The first quasar redshift, $\Delta\lambda/\lambda = 0.16$ for 3C 273, was measured in 1963 by Maarten Schmidt and others. By 1968–1969, about 70 were known, and Geoffrey and Margaret Burbidge remarked, first, that there seemed to be a great many objects with $z = 1.95$ and, second, that there was another major peak at $z = 0.061$ and smaller ones at its multiples of 0.122, 0.183, and so on up to 0.601. The "$z = 1.95$" effect was amenable to two semi-conventional



Histogram of redshifts of quasars initially identified as radio sources. This removes many (not all) of the selection effects associated with the apparent colors of sources at different z's and with the present or absence of strong emission lines in the wavelength ranges usually observed from the ground. The redshift ranges in which various specific lines are usable is indicated. C IV, for instance (rest wavelength 1909 A) disappears into the infrared at z = 3.4. Geoffrey Burbidge concludes that the sharp peaks in the distribution are not the result of selection effects arising from availability of lines to measure redshifts. (Courtesy G. R. Burbidge)



The scale factor, R(t), for universes with non-zero cosmological constant. The case (upper diagram) with flat space, now thought to be the best bet, goes from deceleration to acceleration through an inflection point (which probably happened not much before z = 1) and so has no coasting phase to pile up redshifts at a preferred value, as would happen in a universe with negative curvature (lower diagram). In either case, we live at a time like X, so that the Hubble constant (tangent to the curve) gives the impression of the Universe being younger than it actually is. The early expansion has R proportional to $t^{2/3}$ *and the late expansion has exponential R(t).*

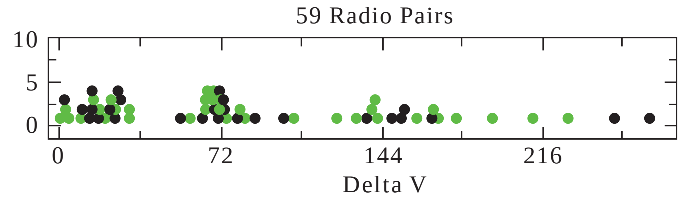
explanations. The first was that $z = 2$ was the maximum that could be expected from a strong gravitational field if the object was to be stable. The second was that $z = 1.95$ might correspond to the epoch during which a Friedmann-Lemaitre universe (one with a non-zero cosmological constant) was coasting at almost constant size, so that we would observe lots of space (hence lots of objects) with that redshift.

In the interim, gravitational redshifts have been pretty clearly ruled out (you can't keep enough low density gas at a single level in your potential well to emit the photons we see), and the peak in $N(z)$ has been diluted as the number of known redshifts has expanded beyond 2000. A cosmological constant is back as part of many people's favorite universes, but (if space is flat) in a form that does not produce a coasting phase, but only an inflection point in $R(t)$.

No conventional explanation for the periodicity at $\Delta z = 0.061$ has ever surfaced, and the situation was not improved over the next decade when, as the data base grew, Geoffrey R. Burbidge reported additional peaks at $z = 0.30$, 0.60, 0.96, and 1.41 and a colleague showed that the whole set, including 1.95, could be fit by $\Delta\log(1+z) = 0.089$. Meanwhile, and apparently independently, Clyde Cowan, venturing out of his usual territory, found quite different peaks separated by $\Delta z = 1/15$ and 1/6. As recently as 1997, another group found several statistically significant peaks in $N(z)$ between 1.2 and 3.2.

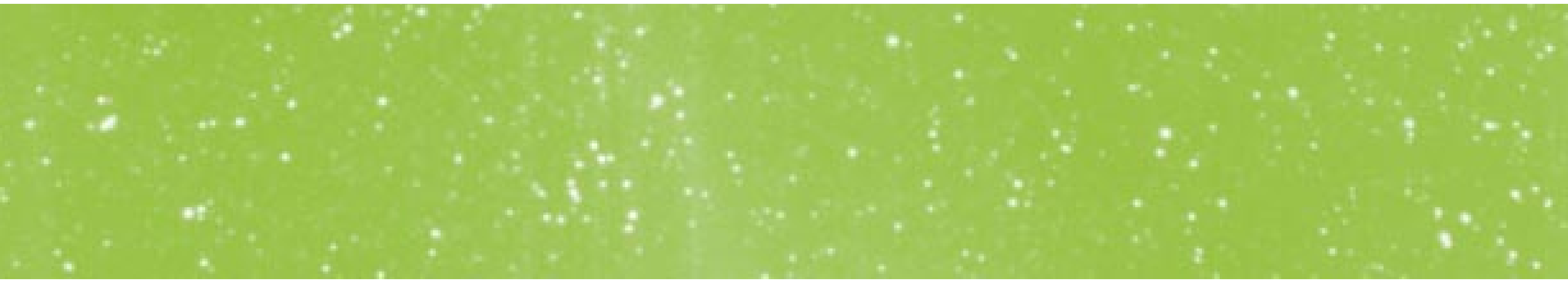
Any attempt to assign statistical significance to these apparent structures in $N(z)$ must take account of two confounders. First, the observed sample is not drawn uniformly from the real population. Quasars have only a few strong emission line from which redshifts can be measured, and these move into, through, and out of observable ranges of wavelength as redshift increases. Second, you must somehow multiply by the probability of all the other similar effects that you didn't find but that would have been equally surprising. The 0.061 effect still appears in the larger data bases of the 1990s, at least when the analysis is done by other supporters of non-cosmological redshifts and quasi-steady-state universes. It does, however, need to be said (and I say it out from under a recently-resigned editorial hat) that the analyses require a certain amount of work, and that it is rather difficult to persuade peopIe who are not violently for or against an unconventional hypothesis to do the work, even as referees.

At the same time the Burbidges were reporting $z = 1.95$ and 0.061 structures, another major player was sneaking up on quantization with much finer intervals. William



A data sample showing redshift quantization on the (roughly) 72 km/sec scale. The points represent differences in velocities between close pairs of galaxies. An extended discussion of the development of the observations and theory of quantization at intervals like 72 and 36 km/sec is given by William Tifft in Journal of Astrophysics and Astronomy 18, 415 (1995). The effects become clearer after the raw data have been modified in various ways. [Courtesy William G. Tifft, Astrophysics and Space Science 227, 25 (1997)].

Tifft of the University of Arizona had started out by trying to measure very accurately the colors of normal galaxies as a function of distance from their centers (one way of probing the ages, masses, and heavy element abundances of the stars that contribute most of the light). In the process, he ended up with numbers he trusted for the total apparent brightnesses of his program galaxies. He proceeded to graph apparent brightness vs. redshift as Hubble and many others had done before him. Lo and behold! His plots were stripy, and, in 1973 he announced that the velocities of ordinary nearby galaxies were quantized in steps of about 72 km/sec ($z = 0.00024$). Admittedly, many of the velocities were uncertain by comparable amounts, and the motion of the solar system itself (about 30 km/sec relative to nearby stars, 220 km/sec around the center of the Milky Way, and so forth) was not negligible on this scale. In the intervening quarter of a century, he has continued to examine more and more data for more and more galaxies, ellipticals as well as spirals, close pairs, and members of rich clusters, as well as nearly isolated galaxies, and even the distributions of velocities of stars within the galaxies. He has also devoted attention to collecting data with uncertainties less than his quantization interval and to taking out the contribution of our own many motions to velocities seen in different directions



in the sky. Some sort of quantization always appears in the results. The interval has slid around a bit between 70 and 75 km/sec and some submultiples have appeared in different contexts, including 36 and 24 km/sec and even something close to 6 km/sec. But the phenomenon persists.

A pair of astronomers at the Royal Observatory Edinburgh looked independently at some of the samples in 1992 and 1996. They found slightly different intervals, for example, 37.22 km/sec, but quantization none the less. A 1999 variant from another author includes periodicity (described as quantization) even in the rotation speeds of normal spiral galaxies.

Tifft's Arizona colleague W. John Cocke has provided some parts of a theoretical framework for the 72 (etc.) km/sec quantization. It has (a) an exclusion principle, so that identical velocities for galaxies in close pairs are at least very rare if not forbidden and (b) some aspects analogous to bound discrete levels on the atomic scale, with continua possible only for velocity differences larger than some particular value. The quantization is, then, responsible for the large range of velocities observed in rich clusters of galaxies which would then not require additional, dark matter to bind them.

Am I prepared to say that there is nothing meaningfuI in any of these peaks and periods? No, though like the race being to the swift and the battle to the strong, that's how I would bet if it were compulsory. There is, however, a different kind of prediction possible. Most of the major players on the unconventional team(s) are at, beyond, or rapidly approaching standard retirement ages. This includes Cocke and Tifft as well as the Burbidges, H. C. (Chip) Arp, a firm exponent of non-cosmological (though not necessarily quantized) redshifts, and the three founders of Steady State Cosmology, Fred Hoyle, Thomas Gold, and Hermann Bondi. Meanwhile, very few young astronomers are rallying to this particular set of flags. Whether this reflects good judgment, fear of ostracism by the mainstream astronomical community, or something else can be debated. But it does, I think mean that periodic, quantized, and non-cosmological redshifts will begin to disappear from the astronomical literature fairly soon.

QUANTUM GRAVITY, QUANTUM COSMOLOGY, AND BEYOND

The further back you try to look into our universal past, the further you diverge from the regimes of energy, density, and so forth at which existing physics has been tested. General relativity is said to be non-renormalizable and nonquantizable, so that some other description of gravity must become necessary and appropriate at least when the age of the Universe is comparable with the Planck time of 10^{-43} sec, and perhaps long after. One prong of the search for new and better physics goes through attempts (via string theory and much else) to unify all four forces, arguably in a space of many more than three dimensions.

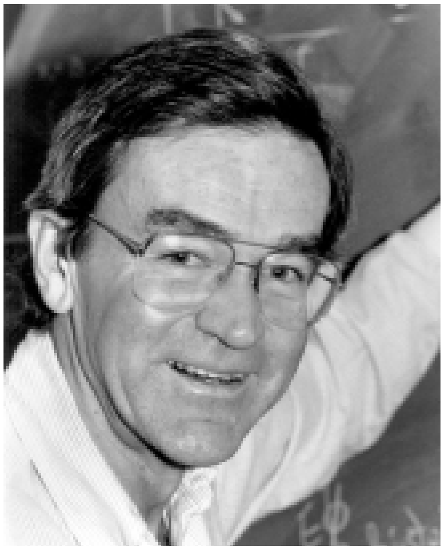
A very different approach is that of quantum cosmology, attempting to write down a Schrödinger-like (Klein-Gordon) equation for the entire Universe and solve it. It is probably not a coincidence that the Wheeler (John Archibald)-DeWitt (Bryce S.) equation, governing the wave function of the Universe, comes also from 1967–1968, when the first claims of periodic and quantized redshifts were being made. The advent of quasars with redshifts larger than one and of the microwave background had quickly made the very large, the very old, and the very spooky all sound exciting.

The difference between the quanta in this short section and in the previous long ones is that quantum gravity and quantum cosmology are respectable part-time activities for serious physicists. The papers appear in different sorts of journals, and the authors include famous names (Hawking, Linde, Witten, Schwartz, Greene, Vilenkin, and others) some of whose bearers are considerably younger than the velocity quantizers and the present author.

This last adventure in astronomical quantization still has most of its bright future ahead of it.

Where to find more:
P. J. E. Peebles, **Principles of Physical Cosmology**, Princeton University Press, 1993 is the repository of how the conventional models work and why some plausible sounding alternatives do not. Some early fractal cosmologies are discussed by E. R. Harrison in **Cosmology: The Science of the Universe**, 2nd edition, Cambridge University Press, 2000. The lead up to Bode's law appears in M. A. Hoskin, **The Cambridge Concise History of Astronomy**, Cambridge University Press, 1999.

CONTRIBUTORS



JAMES BJORKEN (Bj) is best known for playing a central role in the development of the quark-parton model at SLAC from 1963 to 1979. A graduate student at Stanford University, he emigrated to SLAC with his thesis advisor, Sidney Drell, in 1961. During that period they collaborated on a pair of textbooks, of which *Relativistic Quantum Mechanics* is the more beloved.

In 1979 Bj left for a ten-year hiatus at Fermilab where he served as Associate Director of Physics. Shortly after returning to SLAC, he became involved in an experimental initiative at the SSC. Since then he has returned to the world of theoretical physics.

Bj was influential in revamping the *Beam Line* and served on the Editorial Advisory Board for a record seven years. He retired from SLAC in 1999 and is currently building a house in Driggs, Idaho.

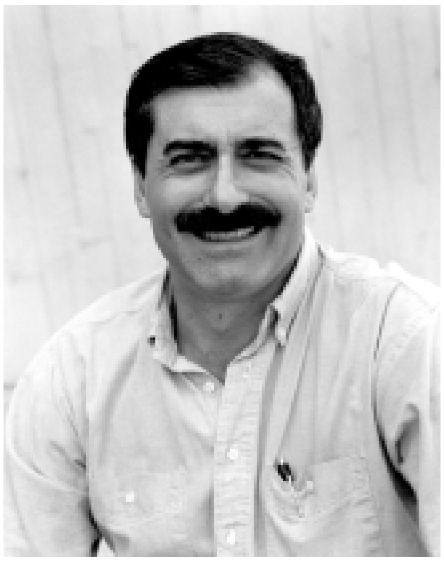
CATHRYN CARSON is a historian of science at the University of California,Berkeley, where she directs the Office for History of Science and Technology. Her interest in the history of quantum mechanics began with an undergraduate thesis at the University of Chicago on the peculiar notion of exchange forces. By that point she had realized that she preferred history to science, but she found herself unable to stop taking physics classes and ended up with a master's degree. She did her graduate work at Harvard University, where she earned a Ph.D. in history of science. At Berkeley she teaches the history of physics and the history of American science.

Recently she has been working on Werner Heisenberg's public role in post-1945 Germany, the history of the science behind nuclear waste management, and theories and practices of research management.

CHARLES H. TOWNES received the 1964 Nobel Prize in physics for his role in the invention of the maser and the laser. He is presently a professor in the Graduate School at the University of California, Berkeley, and engaged in research in astrophysics.

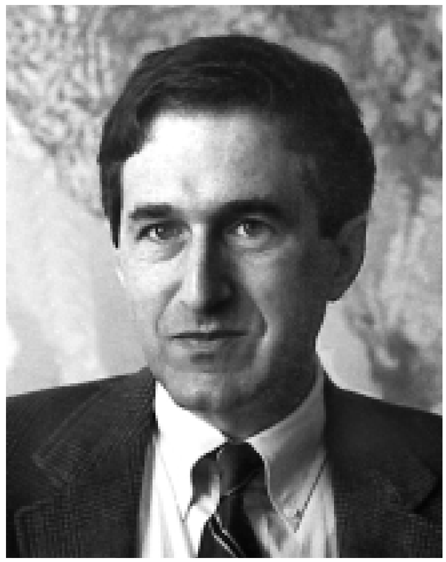
Townes received his Ph.D. in 1939 from the California Institute of Technology and was a member of the Bell Telephone Laboratories technical staff from 1939 to 1947. He has also held professorships at Columbia University and the Massachusetts Institute of Technology, and served as an advisor to the U.S. government.

His many memberships include the National Academy of Sciences, the National Academy of Engineering, and The Royal Society of London. His many awards include the National Medal of Science, the National Academy's Comstock Prize, and the Niels Bohr International Gold Medal, as well as honorary degrees from 25 colleges and universities.



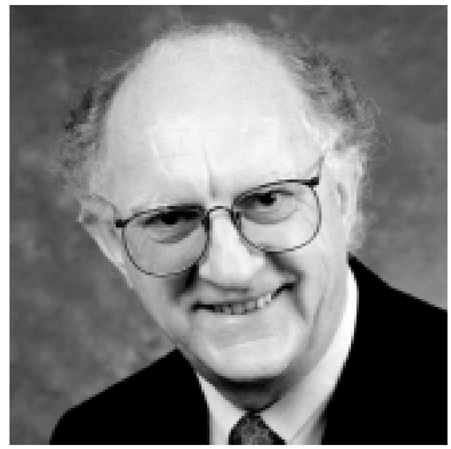
Master of the Universe, EDWARD W. KOLB (known to most as Rocky), is head of the NASA/Fermilab Astrophysics Group at the Fermi National Accelerator Laboratory as well as a Professor of Astronomy and Astrophysics at The University of Chicago. He is a Fellow of the American Physical Society and has served on editorial boards of several international scientific journals as well as the magazine *Astronomy*.

The field of Kolb's research is the application of elementary particle physics to the very early Universe. In addition to over 200 scientific papers, he is a co-author of *The Early Universe*, the standard textbook on particle physics and cosmology. His new book for the general public, *Blind Watchers of the Sky*, winner of the 1996 Emme award from the American Astronomical Society, is the story of the people and ideas that shaped our view of the Universe.



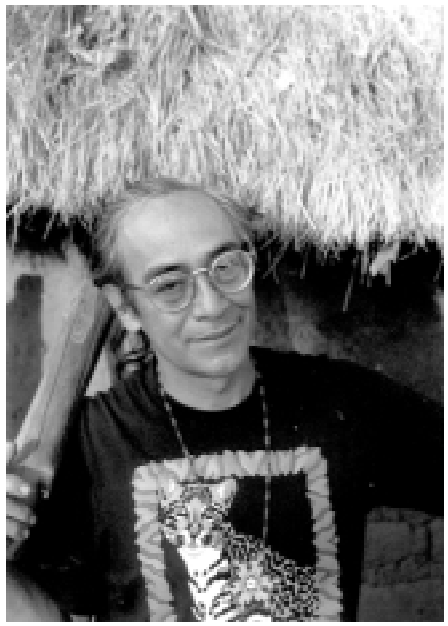
ROBERT L. JAFFE is Professor of Physics and Director of the Center for Theoretical Physics at the Massachusetts Institute of Technology. His research specialty is the physics of elementary particles, especially the dynamics of quark confinement and the Standard Model. He has also worked on the quantum theory of tubes, the astrophysics of dense matter, and many problems in scattering theory. He teaches quantum mechanics, field theory, mechanics, and electrodynamics at the advanced undergraduate and graduate levels.

Jaffe is a Fellow of the American Physical Society and the American Association for the Advancement of Science. He has been awarded the Science Council Prize for Excellence in Teaching Undergraduates, the Graduate Student Council Teaching Award, and the Physics Department Buechner Teaching Prize.



JOHN CLARKE has been in the Physics Department at the University of California, Berkeley and at the Lawrence Berkeley National Laboratory since 1968. He has spent most of his career doing experiments on superconductors, developing superconducting quantum interference devices (SQUIDS), and using them to conduct a wide variety of measurements. Among his current interests are more sensitive detectors for axions, detecting magnetically labeled cells, and mapping magnetic fields from the heart.

He is a Fellow of the Royal Society of London. He was named California Scientist of the year in 1987, and he received the Keithley Award from the American Physical Society in 1998 and the Comstock Prize in Physics from the National Academy of Sciences in 1999.



VIRGINIA TRIMBLE's first published paper dealt with the slopes of the so-called air shafts in Cheops' pyramid and their possible astronomical significance. An alternative explanation is that the slopes are an inevitable consequence of the height: depth ratio of the stone blocks used (a ratio of small whole numbers). The drawing, in the style of a Coptic tomb portrait, was done in 1962 in colored chalk by the originator of the project, the late Alexandre Mikhail Badawy.

A recurring theme in cover artist DAVID MARTINEZ's work is the link between modern scientific knowledge and ancient magical vision. His themes are drawn from both modern and ancient sources, and he is equally inspired by pioneering scientists and by Mother Nature in her various guises. He became interested in mathematics and physics in his teens but only developed his artistic talents in middle age.

Martinez has been active for many years with La Peñ, a Latino arts organization in Austin, Texas. He developed "The Legends Project" with them to teach art and storytelling to at-risk children. He is currently doing research for two paintings, one about Gaston Julia and the other about computers featuring John von Neuman, Alan Turing, John Mauchly, and Presper Eckert.

DATES TO REMEMBER

Nov. 6–9 22nd Advanced ICFA Beam Dynamics Workshop on Ground Motion in Future Accelerators, Menlo Park, CA (robbin@slac.stanford.edu or http://www-project.slac.stanford.edu/lc/wkshp/GM2000/)

Nov. 6–10 2000 Meeting of the High Energy Astrophysics Division (HEADS) of the American Astronomical Society (AAS), Honolulu, Hawaii (Eureka Scientific Inc. Dr. John Vallerga, 2452 Delmer St., Ste. 100, Oakland, CA 94602-3017 or head2k@netcom.com)

Nov. 11–21 International School of Cosmic Ray Astrophysics. 12th Course: High Energy Phenomena in Astrophysics and Cosmology, Erice, Sicily (Ettore Majorana Centre, Via Guarnotta 26, I-91016 Erice, Sicily, Italy or hq@emcsc.ccsem.infn.it and http://www.ccsem.infn.it/)

Nov. 12–15 10th Astronomical Data Analysis Software and Systems (ADASS 2000), Boston, Massachusetts (adass@cfa.harvard.edu or http://hea-www.harvard.edu/ADASS/)

Dec 2–7 International School of Quantum Physics. Third Course: Advances in Quantum Structures 2000, Erice, Sicily (Ettore Majorana Centre, Via Guarnotta 26, I-91016 Erice, Sicily or hq@emcsc.ccsem.infn.it and http://www.ccsem.infn.it/)

Dec 3–8 11th Conference on Computational Physics 2000: New Challenges for the New Millennium (CCP 2000), Brisbane, Australia (http://www.physics.uq.edu.au/CCP2000/)

Dec 11–15 20th Texas Symposium on Relativistic Astrophysics, Austin, Texas (wheel@hej3.as.utexas.edu or http://www.texas-symposium.org/)

Dec 18–22 International Symposium on The Quantum Century: 100 Years of Max Planck's Discovery, New Delhi, India (Director: Centre for Philosophy and Foundations of Science, S-527 Greater Kailash-II, New Delhi, 110048, India or q100@cpfs.org and http://education.vsnl.com/cpfs/q100.html)

2001

Jan 8–Mar 16 Joint Universities School. Course 1: Physics, Technologies, and Applications of Particle Accelerators (JUAS 2001), Archamps, France (ESI/JUAS, Centre Universitaire de Formation et de Recherche, F-74166, Archamps, France or juas@esi.cur-archamps.fr and http://juas.in2p3.fr/)

Jan 15–26 US Particle Accelerator School (USPAS 2001), Houston, Texas (US Particle Accelerator School, Fermilab, MS 125, Box 500, Batavia, IL 60510, USA or uspas@fnal.gov and http://www.indiana-edu/~uspas/programs/)

Feb 19–23 4th International Conference on B Physics and CP Violation (BC4), Ago Town, Mie Prefecture, Japan (A. I. Sanda, Theoretical Physics, Nagoya University, Furo-cho, Chikusa-ku, Nagoya City, Aichi Prefecture, Japan or sanda@eken.phys.nagoya-u.ac.jp and http://www.hepl.phys.nagoya-u.ac.jp/public/bcp4)