Maria Sklodowska Curie: Copernicus of the World of the Small

The last century of physics is examined, some of its achievements are assessed, and the road ahead is surveyed.

John Archibald Wheeler

The month of November 1867 that brought Maria Sklodowska into the world saw James Clerk Maxwell winning new insight into the laws of electromagnetism. Four years later, in the month of October, while Maria sat pouring water from one bottle to another and asking her childhood questions about how and why, Maxwell was delivering his introductory lecture on experimental physics at Cambridge University. After describing the new facilities and stressing the importance of experimental work for the young man and for society, Maxwell offers his vision of physics.

"Two theories of the constitution of bodies have struggled for victory with various fortunes since the earliest ages of speculation: one is the theory of a universal plenum, the other is that of atoms and void." Maxwell went on to note that "the molecule . . . is a very different body from any of those with which experience has hitherto made us acquainted.

"In the first place its mass, and the other constants which define its properties, are absolutely invariable; the individual molecule can neither grow nor decay, but remains unchanged amid all the changes of the bodies of which it may form a constituent.

"In the second place it is not the only molecule of its kind, for there are innumerable other molecules, whose constants are not approximately, but absolutely identical with those of the first molecule, and this whether they are found on the earth, in the sun, or in the fixed stars.

". . . I am forced to believe that these molecules must have been made as they are from the beginning of their existence. . . . [The] idea of the existence of unnumbered individual things, all alike and all unchangeable, is one which cannot enter the human mind and remain without fruit."

Maxwell concludes with the question, "But what if these molecules, indestructible as they are, turn out not to be substances themselves, but mere affections of some other substance . . . a uniformly dense *plenum* . . . ?

Four themes in Maxwell's account deserve attention as representative of physics a century ago. First, he was stating his belief in the indestructibility of the atom at the very time that a little girl in Warsaw had started—without herself yet knowing it—on the road to radium and the transmutation of the atom.

Second, Maxwell is modest about electromagnetism. Hardly a word does he say about that branch of physics, and nothing of his own contribution to it. He may have thought of the electromagnetic field as the magic "plenum" out of which every material object is to be constructed, but he does not make this identification in print. Not only Maxwell was modest about electromagnetism 100 years ago. Everyone was. As late as 1900, and despite the achievements of Hertz, most German universities considered electromagnetism so little important as not to deserve any course of lectures. Even the great Kelvin declared in 1903 that he could not believe Maxwell's theory.

Third, Maxwell says nothing of the possibility that one simple law might account for the structure of every molecule and for all of chemistry. Reason enough there was in his day to discount such ideas. In the first half of the 19th century the great chemist Berzelius had proposed that all chemical forces are but manifestations of electric forces. The idea excited investigations by many workers. Eventually the hypothesis was discredited. The homopolar bond: how can one oxygen atom attract another oxygen atom if identical electric charges repel? Homopolar forces, ionic forces, Van der Waal's forces, valence forces: how can all this variety of magnitudes and particularities possibly be compatible with electric forces, pure and simple? No wonder that Maxwell had turned from the mystery of the individual molecule to the safer ground of statistical mechanics! To him the domain of the small had become a crowd of flying molecules, colliding with one another, those collisions described by one or another empirical law of force. It was a world of black box machinery. If there was a great principle behind it all, that principle was hidden by a hundred details.

Finally, despite all the complexities of phenomena as they appear to the eye, Maxwell held fast to the long-term dream of an underlying unity. Yet to him unity meant not so much one law as one substance. Can we capture in a single word the physics of 100 years ago as we see it through the eyes of Maxwell? How better can we name it than the physics of *substance*? The elementary substances were indestructible. In the structure of substances electromagnetism played a minor role or no role at all. The varied substances found in nature might or might not be made of one common substance.

Law above Substance

From a physics of substance we have moved far in 100 years toward a physics of law. The study of substance revealed law. Law in turn explained substance. Three laws the great investigators gave us: the relativity principle, both special and general; the quantum principle; and electromagnetism.

Electromagnetism, already discovered, was in effect rediscovered when at last it was taken seriously in the world of the small. To that end no one contributed more than Marie Curie. Without her radium where would Rutherford and Marsden have found their projectiles? How would one have penetrated to the universal electric law at the heart of every substance?

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To the great discovery of the quantum principle nothing drove Planck more surely than his determination of many years to study a thermal property of nature free of all reference to solid state physics and free of unsolved issues about the constitution of atoms and molecules. That each law came to light only out of abstractification away from the properties of particular substances shows nowhere more clearly than in the well-known history of relativity.

The unbounded dominion of a basic physical law never ceases to be a source of awe. Who 100 years ago, measuring the attraction between electric charges, and testing the Coulomb law at distances from meters to millimeters, could have predicted that it would be proved valid in 1911 to 10^{-11} cm, in 1933 to 10^{-13} cm, and in still later times to still smaller distances? Who expected that the quantum principle would apply to everything from molecules to nuclei, and from an elementary particle to a superconducting loop a meter in circumference? Who that heard Einstein in 1915 could have anticipated that by 1922 general relativity would predict, and predict correctly, long before it was observed, so fantastic a phenomenon as the expansion of the universe?

Colleagues in the Search for Law

If the sad and lonely figure of Mme. Curie touches anyone's heart, and if he hears from those who knew her that she never smiled, let him read her works. A new step forward, by whomever made, captured her admiration. To her the search was one great enterprise; and all searchers, partners. How did she respond to the movement from a physics of substances toward a physics of law? She welcomed the new laws, she followed them, she preached them. Speaking very early in the 1900's of the law of conservation of mass and the law of conservation of energy she says, "Recently an admirable synthesis has made it possible for us to attain a still higher degree of generalization through the union of these two principles, for it has been proved that the mass of a body is proportional to its internal energy." In 1933 she expounds the quantum mechanical theory of penetration through a potential barrier. In her last book, the two-volume treatise on radioactivity that appeared only in 1935, the year after her death, she surveys among other foundation areas of physics both quantum theory and relativity. She emphasizes that "the proper time of a system is the only time that is accessible to experience" and goes on to clarify the distinction between special relativity and general relativity.

Chemistry as Physics and Physics as Chemistry

If abstractification from substance led to simple law, then in turn simple law unraveled the 100 puzzling details of substance. Chemistry became physics —and much of the physics of substance became transformed into a new and broader chemistry. What difference in principle was there after all between the bonding of atoms in a molecule and the binding of atoms in a solid? What distinction between the pairing of electrons in a superconductor and the pairing of electrons in a giant dye molecule? What sets off the photoelectric energy of an electron in a metal from the valence energy of an atomic electron? All of these effects and much besides reduced to the dynamics of fast moving electrons and slow moving nuclei—and to nothing more. If, nevertheless, much of chemistry looked complex, how could it be otherwise when the bindings at stake were the very small residuals of much larger energies!

Complex or not, the mystery of chemistry had to yield once J. J. Thomson had discovered the electron in 1897, and once Niels Bohr had shown in 1913 that this electron moves obedient both to electric forces and to the quantum principle. Still, it was not easy for the imagination to grasp what organizing power the quantum principle possesses. In encounters in the mid-1920's more than one physicist told his colleague from the laboratory across the way, "Your chemistry is now passé. All that jumble can now be explained in terms of electrons and quantum numbers." In more than one case the then justified reply came back, "What makes you think your circular and elliptic orbits have anything to do with chemistry? Have you ever heard of the valence angles of ammonia or the tetrahedral bonds of carbon? Don't ever forget that electrical forces are electrical forces and chemical forces are chemical forces."

Before Heitler and London could explain valence forces, de Broglie, Heisenberg, and Schroedinger had to clarify the quantum principle. Today no one doubts that the Schroedinger wave equation plus simple electrostatics account in principle for all of chemistry. Yet no surer way could be found to stop the advance of chemistry than to require everyone to calculate the wave function of his new compound before making it. Not the contemplation of 600-dimensional configuration space, but the analysis of the regularities between molecule and molecule, proves the fruitful way to make progress. After all, will not an electron revolving within a molecule always provide us with our cheapest analog computer? What better procedure is there than to use nature's own computer when the energy of binding is the very small difference between the very much larger total energies of the associated and dissociated states?

If during the life of Marie Sklodowska Curie chemistry learned from physical law to master the machinery of molecules and metals, today chemistry has added the nucleus to its domain of interest. Call it nuclear chemistry or nuclear physics as one will, it is remarkably similar to molecular chemistry and atomic physics in its history and way of thought. In both cases the really rapid advance in understanding only began with the identification of the dynamic entity—the electron in 1897, the missing nucleon in 1933. Approximate orbits and quantum numbers we have for nucleons in the nucleus as for electrons in the molecule. The analysis of the regularities from nucleus to nucleus, like the analysis of the regularities from molecule to molecule, often provides a better answer and deeper understanding than any attempt at a calculation from first principles. We speak with admiration when we speak of nuclear chemistry!

Marie Curie and Nuclear Chemistry

Though the great progress in the chemistry of the nucleus took place after her death, Mme. Curie contributed actively during her life. At the famous Solvay Congress of 1913 she calls attention anew to the mystery of the exponential law of radioactive transformation. She stresses the experimental evidence that an atom, if it has not yet decayed, has not aged at all, no matter how long it has lived. She finds physics forced "to look in the interior of the atom for the element of disorder necessary to explain the application of a law of chance." She brings forward the suggestion of Debierne, first, that in the center of the atom there may exist an effective temperature much higher than the external temperature; and second, that the mechanism involved may be identical with that of a monomolecular chemical reaction. She asks us to imagine "a molecule which is moving about in the interior of a box endowed with a tiny hole."

She goes on to say, "When the molecule in the course of its motion meets the hole it leaves the box and the system is radically changed. If we have a great number of boxes each containing one molecule, and if the initial velocities and positions of the molecules are random, it may happen that the escape phenomenon is governed by the rule of chance, even though the constitution of the system itself is relatively simple."

Of all those who have read these wonderfully clearly expressed ideas in recent days, none can have been more astonished to see them than I, who in 1939 had the honor and pleasure in association with Niels Bohr to follow exactly this line of reasoning to its logical conclusion, and end up with the now standard formula for the rate, λ, of a spontaneous transformation in terms of the level spacing D and the effective number of open channels, N:

$$\Gamma = \hbar\lambda = (D/2\pi)N$$

Mme. Curie was in advance of her age. She put forward the right idea to describe nuclear fission at an epoch when she had to do with the leakage of alpha particles through a potential barrier!

No one had a more active concern than she did to distinguish between the nuclear electrons and the extranuclear electrons. When finally it became necessary to conclude that beta rays are formed at the moment of transformation rather than existing in advance, no one could cite more promptly than she the remark of Aston that the smoke does not exist in the pistol until the trigger is pulled!

The Distant Past

In distinguishing between extranuclear electrons and nuclear electrons Marie Sklodowska Curie recognized the proper boundary between molecular chemistry and nuclear chemistry; but she also knew when an idea from the one field could illuminate the other field. Does the abundance of various molecules on the earth today reflect the chemical history of our planet in the recent past? Then may not the abundance of the various nuclei reflect the history of a hotter and more distant past? She ends her book *L'isotopie et les éléments isotopes* with these words, "It is important to continue actively the determination of precise atomic weights, with strict attention to source and purity. If differences appear, they may perhaps give clues to the conditions to which matter was subject in the distant past." Prophetic prelude to all we know today of the building of the elements, thanks not least to Gamow, Fowler, the two Burbidges, and Hoyle!

Forty Years without a New Law

Physics and chemistry continue together today their fruitful married life. Puzzles are encountered, then by skilled hands regularities are found, and through ceaseless activity new knowledge day by day is added to the dominion of old law. Knowledge grows, but the laws do not. Not since the quantum idea flowered into wave mechanics in 1925 has there been a change in fundamental principle—42 years!

Elementary particle physics has given us many beautiful regularities but no new law. Regularities in beta decay, the concept of strangeness and strangeness-conserving currents, marvelous symmetries among the particles, and many another result of recent times excite our imagination. Fascinated as we are, we also ask, are we not seeing simply the unfolding of a third and still more gorgeous branch of chemistry — an "elementary particle chemistry"? We are entranced that the product (charge symmetry) • (parity) mysteriously changes in the decay of the K^o_2 meson, and we are on the alert for something new, with good reason! Did not the mysterious disappearance of energy in the beta decay of atomic nuclei reveal the neutrino? Or in an earlier day, did not the rotation of the plane of polarization of light lead to the discovery of stereochemistry? Chemistry, chemistry, chemistry! The Okubo formula for the masses of the elementary particles—does it not recall other triumphs—Aage Bohr's formula for the energy levels of a nucleus, Racah's formula for the energy levels of an atom, and Bethe's formula for the splitting of levels in the field of force of a crystal? Above all details do we not see in the world of the particles as we see in the other two branches of chemistry the small and complicated residuals of far more powerful energies? What other explanation for structure has anyone ever found? In any case: regularities, yes; beautiful symmetries, yes; but new law, no. Not for 42 years!

Is there a new law still to be found? How tantalizing, for us, not to know—and how fortunate for society! "I must find out." How else could men be brought to bind themselves together in laboratory superorganizations and drive themselves at such a pace? How else build the accelerators, invent the detectors, and develop the particle technology for some thriving new industry of tomorrow?

No one in chemistry or biology feels himself cheated because the relevant physical laws are already known. There is challenge enough, and to spare, in unravelling fresh regularities and in finding new ways to put together old building blocks. So too in physics. And with each passing decade we understand the principles better because we have applied them to more issues. We believe in them all the more firmly because they have never let us down. Neither on the earth nor in space do we know of any cloud to darken their light. The formation of new stars and the explosion of old stars and the greatest variety of events, gigantic in scale and in energy, make the universe incomparably more interesting than any fireworks display that anyone could imagine in his wildest dreams. However, in all this wealth of events not one single effect has been discovered which has led to a new law of physics, and not one single finding has ever been obtained which is generally recognized to be incompatible with existing law.

A Time for Reassessment

In Kelvin's laboratory in Glasgow I saw a few years ago a great rock, and a wire urged to work its way down through that rock by mighty weights. Kelvin had left the wire in tensed duel with its opponent in the hope that the successor of a distant day would see some progress and measure the viscosity of rock. The new director spoke of the laboratory's desperate need for more space. He asked an associate, "How long has this rock sat here?" "Forty years," he was told. "Forty years?" came his response. "We will give it one more week!"

We have waited 42 years. Shall we

too wait another week? And if no new law turns up, when then? If one laboratory director can reexamine the experiment that he inherited from another, may not one generation of investigators reexamine the "plan" of physics handed down by an earlier generation? Who among us has sworn eternal allegiance to the doctrine that there are endless great new laws around the corner? Or six? Or even one? No, our thinking has been locked to the "around the corner plan" of physics, not by any attractions of an endless search, but by bewilderment about the alternative. And what a bewildering and even stupefying alternative it is! (i) All the overarching principles are already in hand. (ii) Relativity, electromagnetism, and the quantum principle supply the entire backbone of physics. (iii) Einstein's vision is to be taken seriously, that particles, rather than being foreign objects immersed in geometry, are manufactured out of geometry—no other building material being available. (iv) A particle is a quantum state of excitation of space, a "geometrodynamical exciton." (v) Elementary particle couplings in all their variety, strong, intermediate, and weak, and with all their specificities, are geometrodynamical in origin, as chemical forces of the most diverse intensities, and most marvelous directivities, are electrical in origin. In brief, Einstein's vision in today's translation—the only alternative that we know to the "around the corner plan" of physics—is of unprecedented scope. No wonder it is fascinating to contemplate, supremely challenging to translate into calculations, and premature to assess! Theory, no; vision, yes; a geometrodynamical vision.

As we weigh the one plan of physics and then the other, over and over, in the days and years ahead, may the face of Marie Sklodowska Curie remain in our thoughts. We see her in her later years, packing her suitcase with such happiness for a Solvay Congress, where she would walk and talk again with Lorentz, Planck, Einstein, Ehrenfest, and Bohr.

We see the magic circle and see Planck speaking. He repeats his great and familiar message. There is only one truly fundamental length in nature; a length free of all reference to the dimensions and rate of rotation of the planet on which we happen to live; free of any appeal to the complex properties of any solid, liquid, or gas; free of every reference to the mysterious properties of any elementary particle; what we call today the Planck length,

$$L = (\hbar G/c^3)^{1/2} = 1.6 \times 10^{-33} \text{ cm},$$

and what we identify with the characteristic scale of the quantum fluctuations in the geometry of space.

The light shifts, the figures are regrouped, and Einstein is giving his famous account of the quantum fluctuations that pervade the electromagnetic field in every part of space, forerunner of modern quantum electrodynamics—the greatest triumph of theoretical physics since World War II—and happy guide to the meaning of quantum fluctuations in the geometry of space at the Planck scale of distances.

The Solvay Congress fades away, we are in an old shed in Paris, and we see a young woman working intently at her radium. She gave us the projectiles to penetrate a new world of small distances. She did more than anyone to open the door to 10^{-13} cm, as her countryman Copernicus did more than anyone to alert us to movement and meaning at the previously unimaginable distance of 10^{+13} cm. Today, thanks not least to these great investigators, we see in our mind's eye each decade of the distance scale alive with its own special activities, from the expansion of the universe at 10^{28} cm to the growth of a crystal at 10^{-1} cm, and from the collapse of a white dwarf star at 10^{8} cm to the form factor of the proton at 10^{-16} cm. Copernicus directed our gaze out to the domain of the unbelievably remote, and today we have come close to plumbing the greatest distances that we know how to conceive. The discoverer of radium by her life and work directs our gaze down to the world of the small. There many new decades of the distance scale still wait to spring into life and meaning, all the way from 10^{-16} cm to Planck's 10^{-33} cm. Marie Sklodowska Curie is our Copernicus in the still continuing voyage of exploration into the world of the unbelievably small.