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PERCY WILLIAMS BRIDGMAN

1882—1961

A Biographical Memoir by
EDWIN C. KEMBLE AND FRANCIS BIRCH

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PERCY WILLIAMS BRIDGMAN was a brilliant, intense, and dedicated scientist. His professional career involved him in three distinct, but closely related, kinds of activity. His early invention of a self-sealing and leak-proof packing opened up a virgin field for experimental exploration in the physics of very high pressures. In work of this kind he had no real competitor, but remained preeminent throughout a lifetime of vigorous and fruitful investigation. His second continuing interest grew out of the first. It did not take him long to discover in the technique of dimensional analysis an essential theoretical device needed in the planning of his experimental program. His success in eliminating what he regarded as metaphysical obscurities in that theory was the lure which eventually launched him on a career of philosophical analysis. In a period of perplexity and paradox in the field of physics, the basic lucidity of his operational point of view was of great value to students and fellow scientists all over the world. The third channel of his activity was that of classroom teaching. His classes were small, but for the young physicists who attended them they were an unforgettable experience. The penetration and tough-minded integrity of his thought, and his never-ceasing habit of probing the limits of scientific knowledge gave his students a heightened sense of the meaning of scientific understanding.

Bridgman's outstanding personal characteristics were the simplicity, directness, and rugged independence of his thinking and the single-minded tenacity with which he directed his life toward its central purposes. He refused to permit either self-indulgence, the demands of society, or the call of a faculty committee to divert his energy from his objectives as an experimenter, teacher, and apostle of clear-headed thinking.

Over Bridgman, the individualist, the scientific fashions of the day had but little influence. In a period when scientific thinking was dominated by the novel and paradoxical conceptions of relativity and the quantum, his laboratory was a place for the study of the mechanical and electrical properties of matter under the highest pressures his ingenuity could realize. He was a pioneer, but his field of exploration was one to which the new ideas had as yet little immediate application. To be sure, he welcomed the new conceptions which set the stage for his philosophical analysis, but he never joined the army of physicists who devoted themselves to the interpretation and exploitation of the quantum.

In his time a revolution in the relation of science to society produced a mushroom growth of large-scale scientific projects carried forward by teams of scientists and financed by government or industry. Bridgman, however, had no interest in the building of scientific empires. Throughout each academic year he worked steadily in his private laboratory and machine shop, taking little time off except for classes. In the summer he sought refuge with his family in the White Mountains. There, in an isolated study among the trees, were written both the papers reporting his experimental results and the essays on scientific logic and social criticism that made him famous. He preferred to work alone; his papers and books described his own experiments and recorded his own thoughts. Rarely did any of his papers bear the name of a collaborating author.

Percy Williams Bridgman was born in Cambridge, Massachusetts, on April 21, 1882. Both parents came of old New England stock. His father, Raymond Landon Bridgman, an author as well as a newspaperman assigned to statehouse affairs, was a profoundly religious and idealistic man—one of the first to advocate a world state. His mother, Mary Ann Maria Williams, was of "a more conventional, sprightly, and competitive" turn of mind.

While Percy was still a small child, the family removed to Auburndale in the town of Newton, a community with an exceptionally fine public school system in which the boy received his elementary and high school education.

In his school years Bridgman was a shy, proud youngster who loved to excel and was a keen competitor on the playground, in the classroom, and over the chess board. At home there were household and garden chores as well as card games and family music. Religion meant a great deal to the family; the Bible was read every morning, and attendence at the Congregational Church was taken as a matter of course. Though it was a matter of deep sorrow to his father that Percy did not feel that he could join the church, later Mr. Bridgman also expressed pride that his son had followed his conscience.

Entering Harvard College in 1900, Peter, as he came later to be known, chose a program of study strongly concentrated in mathematics, physics, and chemistry. The normal requirement for graduation at that time was the completion of a program of seventeen "full courses,"[1] but Bridgman managed to squeeze twenty-three such courses into his four years of undergraduate study. He was awarded an A.B. *summa cum laude* in 1904.

His entire academic and scientific career reflected an unflagging devotion to science formed early in life. He never left

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[1] Harvard never did adopt the semester-hour unit of credit used in most American colleges.

Harvard, but stayed on in the Department of Physics, first as a graduate student (A.M. 1905, Ph.D. 1908) and then as a staff member. He was appointed Research Fellow in 1908, and thereafter Instructor in 1910, Assistant Professor in 1913, Professor in 1919, Hollis Professor of Mathematics and Natural Philosophy in 1926, and finally Higgins University Professor in 1950. His retirement and appointment as Professor Emeritus came in 1954 at the age of seventy-two, after forty-six years of university service.

In 1912 he was married to Olive Ware, of Hartford, Connecticut, daughter of Edmund Asa Ware, founder and first president of Atlanta University. Her gifts of mind and personality complemented his and made their home a harmonious one for a half century of married life together. Except for a brief period during World War I the Bridgmans resided in Cambridge with their two children, Jane and Robert. The family took full advantage of the opportunities for mountain climbing from their summer home at Randolph, New Hampshire. On these expeditions Peter frequently led the way at a pace that taxed the capacity of his companions and earned him a reputation in the local mountaineering circle.

When his daughter was married to the mathematician Bernard Osgood Keepman, in 1948, Bridgman composed the marriage service and secured the necessary authorization to perform the ceremony himself as a temporary justice of the peace.

Bridgman's basic talent as a penetrating analytical thinker was combined with a fertile mechanical imagination and exceptional manipulative dexterity in the ordinary mechanical arts. He took much pride in the opulence of the flower and vegetable gardens that provided his chief avocation during the summer. A skillful amateur carpenter and plumber, he scorned to call in professional assistance to solve household mechanical problems since he could take care of them more neatly himself. He was fond of music and made constant use of his piano as a means of relaxation.

Bridgman's early papers give no explanation of his interest in high pressures. Possibly he was influenced by Professor Theodore Richards of the Chemistry Department, who had measured the compressibility of elements to pressures of about 500 atmospheres; he may have been influenced by Professor Wallace Sabine, with whom he took a research course in "Heat and Light" for four years. Bridgman at first intended to investigate the effect of pressure upon the indices of refraction of liquids, but he was diverted from this plan by his success in developing new high-pressure techniques and never returned to the original problem. In his brief "Autobiographical remarks" filed with the National Academy of Sciences, under the heading "Discoveries which you regard as most important," Bridgman wrote: "Doubtless the most influential single discovery was that of a method of producing high hydrostatic pressure without leak. The discovery of the method had a strong element of accident."

His first three papers, published in successive issues of Volume 44 of the *Proceedings of the American Academy of Arts and Sciences* (1908-1909), laid the foundation for years of later work. The maximum pressure attained, 6500 kg/cm^2, was not much higher than was currently used by other investigators, and was produced inefficiently with a screw compressor turned with a six-foot wrench. Bridgman's first concern appears to have been the establishment of an adequate pressure scale rather than the production of drastically higher pressures. He developed the free piston gauge, or pressure balance, used by Amagat and introduced a more convenient secondary gauge based on the effect of pressure upon the electrical resistance of mercury. The new design of pressure seal, the key to so much subsequent achievement, appears in the discussion of the free piston gauge, with scarcely a suggestion of its importance; indeed he later explained that the self-sealing feature of his first high-pressure packing was incidental to the design of a closure for the pressure vessel so that it could be rapidly assembled or taken apart. The basic advantages of the scheme were realized only afterwards. In the third paper are given new measurements of the compressibility of steel, mercury, and glass, quantities required for various corrections. We recognize already the characteristic Bridgman style: the evident pleasure in the manipulations of shop and laboratory; the meticulous pursuit of the numerous corrections; the experiments with homely mixtures of mercury, molasses, glycerine, and marine glue. None of these early measurements proved definitive; the absolute gauge was soon improved, the mercury gauge was discarded in favor of a manganin wire gauge, the compressibilities were revised. But his rapid succession of publications quickly transformed the field of high-pressure research.

By 1910, a complete redesign of equipment had taken place. The screw compressor was replaced by a hydraulic ram and the new packing was systematically exploited. For the first time, pressures of the order of 20,000 kg/cm^2 and more are reported. Bridgman remarked: "The magnitude of the fluid pressure mentioned here requires brief comment, because without a word of explanation it may seem so large as to cast discredit on the accuracy of all the data." The techniques to be used for the next twenty years had been substantially perfected; they were described more fully in 1914 in a paper on "The Technique of High-Pressure Experimenting."

The essence of Bridgman's leak-proof packing is more easily shown by diagram than explained in words, and is now familiar to all high-pressure experimenters. In principle, its construction ensures that the sealing gasket, of rubber or soft metal, is always compressed to a higher pressure than the pressure to be confined; the high pressure itself is used to tighten the packing, instead of an external screw as in most conventional packings. The ultimate limitation becomes the strength of the metal parts.

Bridgman had the good fortune to begin his experiments at a time when metallurgical advances were providing steels of unprecedentedly high strength; his achievement of still higher pressures in the 1930s was made possible by the development of the cobalt-bonded tungsten carbides. The leak-proof packing would have been of little value with Amagat's steel, but the new alloys permitted spectacular increases of the useful pressure range. After a short period of experimentation with Krupp nickel steel, Bridgman settled on an electric-furnace chrome-vanadium steel (equivalent to the present AISI 6150) for most of his pressure vessels and connecting tubes. In small diameters, this steel can be heat-treated to give a yield point in tension of as much as 270,000 pounds per square inch (psi); it is not, however, a deep-hardening steel and in the sizes of Bridgman's pressure vessels, four or five inches in diameter, the interior remains relatively soft with a yield point of perhaps 150,000 psi, while at the outside, more rapidly quenched, the yield point might reach 220,000 psi. This condition is advantageous for pressure vessels; the elastic limit is reached first in the ductile material near the bore, which can be stretched appreciably without rupture; at the same time, the expansion of the inner part transmits the load to the strong outer parts, which are inefficiently stressed so long as the whole cylinder remains in the elastic range. Thus Bridgman found to his pleasure that pressures could be contained far in excess of predictions based on simple elastic criteria.

Bridgman's laboratory was first established in the basement of the Jefferson Physical Laboratory, built in 1884, and remained there until the construction of the Lyman Laboratory of Physics in 1931. The brick pillars of the old basement served as supports for galvanometers and other equipment, most of it homemade, small, and hand-operated. From the beginning, Bridgman made much of his own apparatus, and his papers contain many useful bits of shop lore which throw light on the amount of labor and persistence underlying his studies. One of the essential components of his pressure system was a pipe connecting the cylinder in which pressure was generated with the cylinder, usually maintained at a different temperature by a liquid bath, in which the material under investigation was compressed. He had to drill the pipe from solid alloy steel bars, as adequate tubing was not yet available. "The inside diameter . . . is 1/16 of an inch, and it is quite possible with a little practise to drill pieces at least 17 inches long. The drill should be cut on the end of a long piece of drill rod; it does not pay to try to braze a long shank onto a short drill. . . . The drill need not be expected to run more than 1/2 of an inch out of center on a piece 17 inches long. . . . It is easy, if all precautions are observed, to drill a hole . . . 17 inches long in from seven to eight hours."

The effort required to maintain these heavily stressed parts was severe. In his paper on "Mercury, Liquid and Solid, under Pressure," Bridgman records (p. 414) that between October 13 and December 3, 1910, "There were at least five . . . explosions; two lower cylinders being burst, two upper cylinders, and one connecting pipe." Each of these components represented several days of shop time and we find here an explanation of the rough appearance of much of Bridgman's equipment: it did not "pay" to invest superfluous labor in parts whose useful life might not exceed a few exposures to pressure. A similar consideration determined the choice of 12,000 kg/cm^2 as the maximum pressure for most of the work up to about 1935. This pressure could be reached repeatedly with little risk of rupture, but beyond this, even a small increase greatly diminished the life of the cylinder.

In 1911 Bridgman described a free-piston absolute gauge usable to 13,000 kg/cm^2, and with this he calibrated the manganin wire gauge originally proposed by Lisell, who had found a linear dependence of the electrical resistance of manganin upon pressure up to 4200 atmospheres. By comparison with his new absolute gauge, Bridgman showed that the linearity continues to at least 12,000 kg/cm^2. As a secondary gauge, the manganin coil proved invaluable, since, unlike the free piston gauge, it could be incorporated in a leak-free system requiring only an insulated electrical connection to an outside measuring device. It requires calibration, however, and whereas in principle the primary gauge can be used for this purpose, it is more convenient to make use of "fixed points" on the pressure scale, like the "fixed points" of a temperature scale commonly used in place of the primary gas thermometer.[2]

One may surmise that Bridgman thoroughly enjoyed the use of his muscles on the pumps and the complete personal control thus exercised over the functioning of his equipment. The manipulations took him from pumps to measuring apparatus—usually a set of electrical bridges or potentiometers requiring telescopic observation of galvanometer deflections—to notebook in which notations were made in his private shorthand, and back to pump for a new cycle. All of this was performed as fast as the various thermal and pressure lags would permit, sometimes on a fixed schedule of time and over periods

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[2] The point most used by Bridgman and many later investigators is the melting pressure of mercury at 0°C, observable as a pressure of discontinuity either of electrical resistance or of volume when these quantities are measured as functions of pressure. The pressure value derived from his 1911 observations, 7640 kg/cm^2, was used as a standard for subsequent calibrations, entering directly into all his measurements of compressibility and other pressure coefficients in which the manganin gauge was used. Redeterminations in the last few years with much more elaborate apparatus suggest an error of possibly 1 percent in this value, Newhall, Abbot, and Dunn (1963) giving 7715.6 kg/cm^2.

of several hours. Much philosophical debate has taken place over the meaning of his term "operational," but his own original meaning must have been closely related to the manifold physical activities of his laboratory, with every adjustment and every measurement dictated by his own mind and controlled by his own muscles.

After the completion of the Lyman Laboratory of Physics midway in Bridgman's experimental career, he was "promoted" to more ample quarters in a suite of rooms in the new building. Here his office was adjacent to his experimental rooms and private machine shop. Mr. Leonard H. Abbot served him as experimental assistant and Mr. Charles Chase as his machinist, but Bridgman himself continued to work with his hands as well as his brain until retirement.

The new laboratory also provided room for his research students, who had previously to find cubbyholes in the maze of the Jefferson basement. There were rarely more than two or three of these at one time; the record shows fourteen doctoral theses on high-pressure topics in addition to several supervised by Bridgman on other subjects. He spent relatively little time on the direction of graduate students and was usually most pleased when least consulted, but was willing to put his mind on real difficulties, and rarely failed to make valuable suggestions when his advice was sought.

Most of Bridgman's measurements may be grouped in a few categories, in each of which successive increases of the pressure range and additions of new substances led to new investigations. The principal topics were compression (59 papers), melting (12), polymorphism (35), electrical resistivity (48), elastic constants (9), thermoelectricity (9), and mechanical properties such as fracture strength and plasticity (37). Besides these there were papers on viscosity (4), thermal conductivity (6), and miscellaneous matters of technique (11). Once a successful method of measurement was developed, Bridgman applied it rapidly to virtually every simple element or compound to which it was applicable. Characteristic titles are: "The compressibility of thirty metals as a function of pressure and temperature"; "Freezing parameters and compressions of twenty-one substances to 50,000 kg/cm^2"; "The resistance of 72 elements, alloys and compounds to 100,000 kg/cm^2." Whole shelves of chemicals were ransacked for some of these studies, and as new standards of purity were attained, many of the measurements were repeated. Bridgman noted the discrepancies which resulted on repetitions and sometimes indicated which measurements were in his opinion to be preferred, but on the whole spent little time in a search for perfect consistency.

This is not the place for a discussion of all the devices employed by Bridgman; later generations of experimenters will perhaps be most impressed by the simplicity of principle of his arrangements, nearly all depending upon pistons, springs, levers, falling weights, combined with direct-current electrical measurements of resistance and potential. Bridgman's special talent was for making these devices operate successfully in the limited spaces of his pressure vessels, and in coping with the innumerable corrections arising from dimensional and other changes under pressure. The vacuum tube played virtually no part in his instrumentation. The electrical parts of the measuring systems, like the pressure systems, were mostly homemade; the readings were made on meter-long slide wires with the aid of reading glasses, and the slide wires were subject to frequent checks for uniformity. The resolution and accuracy attainable with these instruments reached their culmination in the measurements of compression to 100,000 kg/cm^2, made on samples 1/8 inch long and 1/16 inch in diameter, compressed in a miniature tungsten carbide die which itself was subjected to 25,000 kg/cm^2 in an outer pressure system. These measurements are among the most amazing of Bridgman's many astonishing feats. Many of these determinations have since been repeated with remarkably concordant results by the completely independent technique of shock waves.

Bridgman's mastery of laboratory techniques was also applied to the preparation of samples. Reactive materials such as the alkali metals were encased in protective sheaths. A method of growing large single crystals of metals which has been widely used by later workers was described more or less in passing, and the purification of the solid phase by concentration of impurities in the melt, briefly noticed, foreshadowed the later process of zone refining.

Perhaps no aspect of Bridgman's work attracted more general interest than his studies of polymorphism under pressure; in one substance after another, unsuspected and unpredictable new forms were discovered. "Hot ice" was doubtless the most popular, and a railroad official is said to have inquired about the possibility of producing this on a large scale for refrigeration! The large number of new modifications observed within his pressure range led Bridgman to the conclusion, subsequently confirmed, that few of the minerals common at the earth's surface remain stable under the still higher pressures of the interior. His awareness of the importance of his studies for geology and geophysics was greatly stimulated by the interest shown in his work by geologists, especially his friend and neighbor, Reginald A. Daly, whose frequent visits to Bridgman's laboratory are reflected in several papers dealing with rocks and minerals. Bridgman realized, however, that geological problems opened up a whole vista of experiments with complex, unfamiliar materials and high temperatures which he was not prepared to undertake.

An account of his early feeling about this question, related by him, is revealing. After his first few publications on high-pressure research, Bridgman was approached by Arthur L. Day, the farsighted Director of the Geophysical Laboratory of the Carnegie Institution. Day offered him a free hand if he would come to the Geophysical Laboratory, but Bridgman preferred to remain in the Physics Department at Harvard. He felt that Day should not have made such an offer. "I told him that I was interested in pure physics, and he had no right to be," is what many years later he recalled his answer to have been. But Day might well have had the last word: virtually all of Bridgman's work has added to the understanding of the behavior of matter in the earth's depths.

His remaining at Harvard for the better pursuit of pure physics was on a modified schedule: on asking Mr. Eliot if Harvard had a place for a man who did no administrative work or undergraduate teaching so that he could devote more time to research, the answer was, "Yes, if he is good enough." Bridgman took the risk.

In 1932, in cooperation with Daly, Harlow Shapley, L. C. Graton, and others, Bridgman took an active part in initiating a program at Harvard for high-pressure studies devoted to geophysical problems, the first to be established in a university; with variations of emphasis, such studies are now pursued in many universities and industrial laboratories.

His activity on the Committee on Experimental Geology and Geophysics was one of the few diversions which he permitted himself in university affairs. To President Lowell he said, "I am not interested in your college, I want to do research," and got away with it. Committee life in the universities in the prewar days had not, of course, attained its present state of hypertrophy, but even then Bridgman was perhaps unique in his abstention. On the other hand he took an active part in the business of the American Academy of Arts and Sciences, with which he was closely linked in several ways. Nearly all of his investigations were published in its *Proceedings;* he received the Rumford Medal of the Academy in 1917; and from 1907 onward, his work was assisted by small grants from the Rumford Fund. He became a Fellow in 1912, a member of the Rumford Award Committee in 1919, serving to 1952, Vice President of Class I (Mathematics, Physics, Astronomy) from 1940 to 1944, a member of the Board of Editors of *Daedalus* from 1957 to 1961, and a member of several committees concerned with the general implications of science. Bridgman may have felt that he owed this service to the Academy in return for its consistent, if meager, support of his work. The American Academy grants, mainly from the Rumford Fund "for researches in light and heat," amounted to about $400 a year for a number of years, and, with similar aid from the Bache Fund of the National Academy, appear to have constituted most of his financial support up to about 1940. Since most of the grants were awarded for "Investigations of optical and thermal properties under high pressures," we infer that the original intention to study optical properties remained in Bridgman's mind, though it was never realized. Even with allowance for the greater purchasing power of the dollar before 1940, Bridgman's laboratory budget was remarkably small, and the return per dollar astonishingly large.

In both world wars, Bridgman applied his talents to wartime problems. In 1917 he moved to New London to take charge of a research group concerned with the detection of submarines by acoustical methods. A major difficulty was noise produced by a ship's own auxiliary motors which could not be shut down during listening intervals. Bridgman developed a sound-insulating system, which was subsequently widely applied, for mounting these auxiliaries. He also studied the possibility of using large areas of the ship's skin, coupled with receivers installed inside the ship, for the detection of under-water sound; this plan had the advantage of eliminating the need for dry-dock facilities, which were in short supply. The following details have been kindly supplied by Professor Louis B. Slichter: "A . . . design . . . for listening through the skin of the ship involved the use of large circular containers, usually called 'soup plates,' clamped against the skin of the ship with a gasket seal and filled with water. In this water cavity, sound receivers were placed. In May 1917 a multiple unit listening device of this type was installed on the troop ship *George Washington* for use on a trip to Brest. . . . The writer [Slichter] was placed in charge of the detachment of trained listeners who stood watches continuously at this detector [during the voyage]. . . . Apparently because of some mistake made in counting the many deck levels of this great ship, the installation was unfortunately made above the water line, far out of reach of submarine sounds. It seemed best not to emphasize this discouraging discovery, and so the listeners carried on their duties conscientiously in happy oblivion."

Another development, which came too late for World War I but was used extensively thereafter, was based directly upon his high-pressure techniques; this was a method for increasing the yield point of artillery gun barrels by a preliminary stretching with internal hydrostatic pressure, exactly the same procedure, though on an enlarged scale, which he had successfully applied to his pressure vessels. This process made it possible to produce guns from single forgings, instead of the series of shrunk-on tubes formerly required.

Bridgman was a rugged libertarian who anticipated World War II by a private declaration of his own closing his laboratory early in 1939 to visitors from totalitarian states. The following short statement (*Science,* February 24, 1939, p. 179) was handed to any such prospective visitors who presented themselves at his door:

"I have decided from now on not to show my apparatus or discuss my experiments with citizens of any totalitarian state. A citizen of such a state is no longer a free individual, but he may be compelled to engage in any activity whatever to advance the purposes of that state. The purposes of the totalitarian states have shown themselves to be in irreconcilable conflict with the purposes of free states. In particular, the totalitarian states do not recognize that the free cultivation of scientific knowledge for its own sake is a worthy end of human endeavor, but have commandeered the scientific activities of their citizens to serve their own purposes. These states have thus annulled the grounds which formerly justified and made a pleasure of the free sharing of scientific knowledge between individuals of different countries. A self-respecting recognition of this altered situation demands that this practice be stopped. Cessation of scientific intercourse with the totalitarian states serves the double purpose of making more difficult the misuse of scientific information by these states, and of giving the individual opportunity to express his abhorrence of their practices.

"This statement is made entirely on my own initiative and has no connection with any policy of the university."

During World War II he undertook studies of plastic flow in steel related to the penetration of armor by projectiles; much of this work later appeared in his book *Studies in Large Plastic Flow and Fracture.* Measurements of the compressibility of uranium and plutonium were made at the request of the Los Alamos Laboratory.

A characteristic product of Bridgman's desire for intellectual efficiency was his reduction of thermodynamic formulas to tabular form. The ten fundamental thermodynamic functions have 720 first derivatives, among which there exist some eleven billion possible relations. By choosing three experimentally measurable first derivatives as fundamental, viz., compressibility, thermal expansion, and heat capacity, Bridgman was able to compress all of these possibilities to a table of 90 entries, as well as to provide a compact digest of the even more numerous second derivatives. Once and for all, these relationships were made readily available with a great economy of effort.

One of his early teaching assignments was the task of giving two advanced courses in electrodynamics suddenly thrust upon him in 1914 by the death of B. O. Peirce. Years later he commented on the obscurity of the underlying conceptual situation which he found in this area and the intellectual distress which it caused him. His efforts to meet the logical problems of electrodynamics provided the initial stimulus for his subsequent activity as a critic of the logical structure of physics.

His first publication dealing with the logical problems of physics was a 1916 paper on Tolman's newly proposed principle of similitude. In this article he showed—what Buckingham had surmised—that the valid conclusions drawn by Tolman from the rule of similitude can be independently derived by dimensional analysis and that, furthermore, the application of the Tolman rule to gravitational forces leads to an unacceptable result.

Returning to Harvard in the spring of 1920 from the antisubmarine project at New London, he turned his attention once more to the problems of dimensional reasoning, long a subject for sporadic controversy among physicists. Despite forward steps taken by Buckingham,[3] basic issues remained unsettled and Bridgman set to work to put the subject in order. His initial book-length publication, *Dimensional Analysis,* issued in 1922, was the result. It combined the first systematic and critical exposition of the principles involved with a rich variety of illustrative applications.

Basic to Bridgman's formulation of dimensional theory was his insistence that when, for example, we say that the speed of

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[3] Edgar Buckingham, *Phys. Rev.,* 4 (1914):345, 357.

an automobile is 60 mi/hr, the assertion should not be interpreted as meaning that the speed in question is 60 times the ratio of one mile to one hour. "It is meaningless to talk of dividing a length by a time; what we actually do is to operate with numbers which are the measures of these quantities." For this reason he rejected the widely held view that the letter symbols for the different physical quantities in the equations of physics should be considered to represent corresponding physical quantities. It suffices to suppose that the symbols are placeholders for the numerical measure-values of the physical quantities. He recognized the practical convenience of the custom of treating the equations of physics as relations between numbers carrying dimensional unit labels, but considered that to call such labeled numbers "physical quantities" is to introduce an unwarranted and misleading verbalism.

A primary objective of the monograph *Dimensional Analysis* was accordingly to demonstrate that the dimensional properties of the equations of physics can be fully explained on the legitimate assumption that the letter symbols represent mere numbers. Hence the rule of dimensional homogeneity is not to be derived from a metaphysical interpretation of what the equations mean, but from the universal practice among physicists of writing their equations in a form that is *complete,* i.e., a form equally valid for all values of the primary units involved. Following the lead of Fourier, James Thomson, and Buckingham, Bridgman restricted his discussion of dimensional analysis to complete physical equations. The restriction was no handicap, for every physical equation can be put into complete form by the introduction of suitable dimensional constants; every physicist instinctively expresses himself in the language of such equations. Thus dimensional analysis is a technique for taking advantage of the language structure.

Perhaps the most significant of Bridgman's contributions to dimensional analysis was his recognition of the scientific sophistication required for the practice of the technique. The analyst must list all the physical quantities, including dimensional constants, relevant to the solution of the physical problem in hand. Any omission will falsify his result; the inclusion of any superfluous quantity will cheat him of full success. Making the decision requires a broad scientific background. The practitioner of the art must be familiar with the branch of science in which the problem falls and with the basic differential equations which rule that field, for the dimensional constants he must reckon with turn out to be those involved in the differential equations. This means that the specific problems to which dimensional analysis is applicable are those that in principle could be solved analytically with the help of appropriate differential equations.

The foregoing conclusion exposes the limitations of dimensional reasoning and at the same time removes the mystery of its power. Bridgman shows us that the technique owes most of its success in providing its practitioners with unearned information to the unconscious use which they have made of the normal background of the experienced professional scientist. The method is extremely useful, but it does not give the inquirer something for nothing after all.

Bridgman's success in thinking his way through the metaphysical confusions of dimensional analysis encouraged him to turn his attention to the larger task of eliminating similar confusions in the broader field of physics proper. Einstein's discovery that there is no such thing as absolute simultaneity between events at different places was proof that the basic concepts of time and space had been seriously misconceived. This revelation of shabby thinking at the core of physics seemed to Bridgman to call for a critical reexamination of the conceptual structure of physics as a whole. *The Logic of Modern Physics,* issued in 1927, is a report of his early conclusions.

This book was destined to have wide influence on the thinking of a generation of physicists struggling to make sense out of new and revolutionary facts in a time of change. Here his conception of operational analysis as a basic intellectual tool was clearly formulated. Its repercussions spread in time through the whole intellectual world and established the reputation of its author as a penetrating thinker of the first rank. The volume was written in a single half-year of sabbatical leave; Bridgman habitually rationed his time and would not allow himself a longer period of absence from his laboratory. Fortunately he had a natural facility in the use of words, for he rarely indulged in the luxury of rewriting to improve the phraseology of what he had once committed to paper.

The attitude with which he approached his task was one of pure empiricism. For him physics was the quantitative exploration and analysis of physical experience. The discoveries behind the revolution in physics then in progress seemed to prove the total folly of assuming that the possibilities of new experience can be limited by any known *a priori* principles. They showed, moreover, that the central intuitive concepts of physics had been seriously at fault because they had involved unwarranted presuppositions. In his view the time had come for every scientist to analyze afresh the relation between his conceptual apparatus and his actual experience. Only in this way can he hope to escape from the ruts and booby traps embedded in the language he inherits from the past. Specifically, Bridgman called for discontinuance of the practice of defining physical concepts in terms of their assumed properties without prior proof that something corresponding to those properties exists in nature. Since such proof can come only through laboratory activity, it was evident to him that the ultimate meaning of every physical concept is bound up with the physical and mental operations by which it is measured or tested. He took satisfaction in observing that Einstein's original breakthrough was achieved by testing the concept of the simultaneity of widely separated events by an analysis of the *operations* involved in the synchronization of clocks in different locations. In focusing attention on physical and mental operations and activities, Bridgman considered that he was maintaining the closest possible connection between the living reality of scientific experience and the physical theories designed to interpret that experience.

The Logic of Modern Physics includes a reexamination of a number of the key concepts of physics from his operational point of view. For many of his junior contemporaries the reading of its pages was a memorable and exhilarating experience. It swept away a fog of unverified assumptions and gave us a new conception of the possibilities of clear thinking. From it we learned that, when new techniques of measurement open up new domains of experience, the meanings of our concepts are altered. His emphasis on the multiplicity of operational meanings associated with specific scientific terms prepared us to meet new facts with flexible minds. Bridgman helped to free us from the compulsive need of the preceding generation of physicists to find mechanical explanations for all the phenomena of nature. He made no direct contribution to the development of quantum theory, but his point of view did much to alleviate the initial confusion over the paradoxical combination of wave-like and corpuscle-like properties of radiation and matter with which quantum theory is concerned. His thinking made it easier for us to accept the observed behavior of microscopic systems at its face value without trying to force it into a logical mold dictated by the language and categories of macroscopic experience and common sense. He saved our time and energy by pointing out the futility of efforts to find the answers to verbal questions that are in principle beyond the reach of experimental test.

In due course *The Logic of Modern Physics* was followed by other books and papers extending and deepening his critical examination of the concepts and theories of physics. His Princeton University lectures on *The Nature of Physical Theory* were published in 1936. *The Nature of Thermodynamics* followed in 1941 and *A Sophisticate's Primer of Relativity* appeared as a posthumous publication in 1962. In these studies he drew attention away from the apparent precision of the mathematical equations of physics and the seemingly rigorous logic of axiomatically constructed theories to the matrix of crude observations and approximate verbal explanations from which the symbols and equations derive their significance. His relentless probing exposed a surprising penumbra of uncertainty regarding the interpretation of the symbols in thermodynamics, for example, in different physical situations and regarding the limits of applicability of its concepts. He clarified the status of theoretical physics by putting the spotlight on what is unclear and by calling attention to the essential part which language plays in the making of theories.

From the beginning it was evident that the value of an operational analysis of concepts, assertions, and questions is not restricted to physics or the physical sciences. It can be used to help the thinker in any field to distinguish between facts firmly rooted in the ground of experience and pseudo facts which have no such basis. The lesson that it is not what we say that counts, but what we do, is of universal application. In Bridgman's view language which does not meet the operation test is basically spurious and meaningless. Thus, because there is no conceivable way to measure absolute position, it means nothing to ask whether a star is at rest or not. It seemed equally clear to Bridgman that "many of the problems with which the human intellect has tortured itself [are] only pseudo problems" because they can be formulated only in terms of questions that are essentially meaningless. Many of the traditional disputes in the areas of philosophy, religion, and ethics were assigned to this category. Consider, for example, the question of the freedom of the will: "You maintain that you are free to take either the right- or left-hand fork in the road. I defy you to set up a single objective criterion by which you can prove after you have made the turn that you might have made the other. The problem has no meaning in the sphere of objective activity; it relates only to my personal subjective feelings while making the decision."

He recognized that "there is a sense in which no serious question is entirely without meaning, because doubtless the questioner had in mind some intention in asking the question." But if the meaning of a question cannot be pinned down by some imaginable test operation, the question is footless. We should waste no time over it.

Perhaps inevitably, Bridgman found himself under compulsion to apply his point of view to the wider problems of society. He was a single-minded man to whom confusions of meaning, muddle-headedness, self-delusions, and misrepresentations of all kinds were anathema. The test of operational thinking gave him a logical weapon with which to attack the incubus of tangled nonsense which prevents intelligent action in a society interested only casually in the search for truth. In three volumes, *The Intelligent Individual and Society* (1938), *Reflections of a Physicist* (1950), *The Way Things Are* (1959), he used his weapon ruthlessly, giving little quarter as he subjected the traditional absolutist conceptions of duty, responsibility, right, justice, and law to the test of operational meaning.

Through the years the need to find intelligent answers to his own problems and the problems of society grew upon him. In the opening passage of *The Intelligent Individual and Society,* he said: "As I grow older a note of intellectual dissatisfaction becomes an increasingly insistent overtone in my life. I am becoming more and more conscious that my life will not stand intelligent scrutiny, and at the same time my desire to lead an intelligently well ordered life grows to an almost physical intensity." Far from accepting the sharp distinction which the average person draws between moral and intellectual issues, he tended to treat intellectual integrity as the supreme ethical problem facing mankind. In one lyrical passage discussing the effect of the practice of intellectual honesty on the scientific worker, he said: "The ideal of intellectual honesty comes to make a strong emotional appeal; he [the scientist] finds something fine in the selflessness involved in rigorously carrying through a train of thought careless of the personal implications; he feels a traitor to something deep within him if he refuses to follow out logical implications because he sees that they are going to be unpleasant; and he exults that he belongs to a race which is capable of such emotions."

In a note under the title "A Challenge to Physicists," published in the war year 1942, he said: "From a long-range point of view the deepest issues of the present crisis are intellectual. The failure of this country up to the present has been primarily an intellectual failure—intellectual sloth, lack of imagination, and wishful thinking. The crisis of a totalitarian victory is, from the perspective of a thousand years, an intellectual crisis. The day when the human race may evolve into a race capable of the intellectual mastery of its fate will be immeasurably postponed by such a victory. . . . The race will not save itself until it achieves intellectual morale. Perhaps the two chief components of intellectual morale are intellectual integrity and a fierce conviction that man *can* become the master of his fate."

Bridgman's emphasis on the correspondence between the words we use in organizing our experience and the operations which he thought of as atoms of experience brought with it a strong individualistic tone congenial to his temperament. The experience with which each one of us must deal is his own. Operational analysis is basically an introspective process. Bridgman pointed out that the custom of impersonal reporting in scientific work obscures the fact that all the observations, judgments, and interpretations involved in scientific activity are made by individuals. Although public science is created through communication and checking operations, it is preceded by the private science of the individual. Only the individual can have experience and only the individual can think about it. In writing Bridgman's own practice was to make frequent use of first-person pronouns.

In applying his operational method to the problems of society, he began with the proposition that society in general, as well as the scientific community, is simply the sum of the individuals who make it up. On this basis he drew the conclusion that the most important features of society are those to be discovered by the analysis of the relations between each individual and those others who make up the society of which he is a part. There is never any question of Bridgman's integrity or candor. Always a rebel against social controls, even when he realized how necessary they are, he despised the artifices of rationalization by which the leaders of society have always compelled their fellows to keep in step. His minimum code for the regulation of an ideal Bridgmanian Utopia is one that society as we know it could never accept. On the other hand, one of the most deep-seated of the many ailments of the world today is, perhaps, just the lack of intellectual honesty for which Bridgman fought.

To sum up: Bridgman's influence was strongest among scientists, who found his point of view congenial. Much of what he had to say is commonly accepted among them today. His philosophic writing, to be sure, was always iconoclastic and stimulated a good deal of controversy, especially among those philosophers of science who managed to misread his intent. Operational analysis, he had to explain, was proposed as an aid to clear thinking and not as a solution for all the problems of philosophy. Again and again he gave expression to his dislike of the word "operationalism" with its implication of an associated dogma.

He was disappointed as he grew older with the reaction to his attempts to promote operational thinking in the field of the social sciences. Yet he remained a warm, considerate, and courageous person who drew the admiration and affection of all who knew him well.

In the spring and summer of 1961 he became crippled in both legs, with increasingly intense pain and great fatigue. By mid-July an expert diagnosis was at last procured: intractable cancer of major bones, which would inevitably prove fatal in a matter of months or a year. It was characteristic of the man that then he did not hesitate to take his own life. The decision to do so was for him a matter of principle—one which he had faced many years before. In a last note, left in his pocket on the day of his death, he said, "It isn't decent for Society to make a man do this thing himself. Probably this is the last day I will be able to do it myself."

Bridgman was a member of the National Academy of Sciences (1918), the American Philosophical Society, the American Academy of Arts and Sciences, the Washington Academy of Sciences, the American Association for the Advancement of Science, the American Physical Society (president, 1942), foreign member of the Royal Society (London), honorary fellow of the Physical Society (London), a corresponding member of the Academia Nacional de Ciencias, Mexico, and a foreign member of the Indian Academy of Science.

In addition to the 1946 Nobel Prize in physics, he was the recipient of the Rumford Medal of the American Academy of Arts and Sciences (1917), the Cresson Medal of the Franklin Institute (1932), the Roozenboom Medal of the Netherlands Royal Academy (1933), the Comstock Prize of the National Academy of Sciences (1933), the Research Corporation of America Award (1937), and the Bingham Medal of the Society of Rheology (1951).

He held honorary doctor of science degrees from Brooklyn Polytechnic Institute (1934), Harvard University (1939), Stevens Institute of Technology (1941), Princeton University (1950), Yale University (1951), and the degree D. Honoris Causa, Paris (1950).

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KEY TO ABBREVIATIONS

Am. J. Sci. = American Journal of Science
Am. Scientist = American Scientist
J. Am. Chem. Soc. = Journal of the American Chemical Society
J. Appl. Phys. = Journal of Applied Physics
J. Chem. Phys. = Journal of Chemical Physics
J. Colloid Sci. = Journal of Colloid Science
J. Franklin Inst. = Journal of the Franklin Institute
J. Wash. Acad. Sci. = Journal of the Washington Academy of Sciences
Mech. Eng. = Mechanical Engineering
Phil. Mag. = Philosophical Magazine
Philosophy Sci. = Philosophy of Science
Phys. Rev. = Physical Review
Proc. Am. Acad. Arts Sci. = Proceedings of the American Academy of Arts and Sciences
Proc. Nat. Acad. Sci. = Proceedings of the National Academy of Sciences
Psychol. Rev. = Psychological Reviews
Rec. trav. chim. Pays-Bas = Recueil des travaux chimiques des Pays-Bas
Rev. Mod. Phys. = Reviews of Modern Physics
Sci. Monthly = Scientific Monthly
Z. Physik. Chem. = Zeitschrift fuer Physikalische Chemie

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