tion, which work formed the subject of the Bakerian lecture for 1910.

The effect of radiation pressure on dust in the solar system, and the use of the law for the intensity of radiation from a blackbody to estimate the temperature of the planets, also interested Poynting. Other theoretical work involved more thorough discussion of the phase transition between the solid and liquid states (1881) and of osmotic pressure (1896). He developed instruments for research and for lecture demonstration, and performed research confirming his own predictions concerning the behavior of loaded wires under torsion (1905, 1909). Among Poynting's earliest works were statistical studies on drunkenness in England (1877, 1878) and on fluctuation of commodity prices (1884). Besides his Adams Prize essay he wrote *The Pressure of Light* and *The Earth*, and was coauthor with J. J. Thomson of a series of physics textbooks.

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A. E. WOODRUFF

PRANDTL, LUDWIG (*b.* Freising, Germany, 4 February 1875; *d.* Göttingen, Germany, 15 August 1953), *fluid mechanics.*

Prandtl was the founder of boundary layer theory and the originator of the German school of aerodynamics. His own work and that of his many students over half a century made Göttingen University the source of most of the elements of modern fluid mechanics. The notion of the boundary layer, the role of bound vortices in airfoil theory, the foundations of supersonic aerodynamics, explanations of drag coefficients and friction factors for a host of situations, the concept and applications of the turbulent mixing length, and the theory of wakes were results of his work.

Prandtl was the only child of Alexander Prandtl, an engineering professor at the agricultural college at Weihenstephan. Owing to the protracted illness of his mother, the former Magdalene Ostermann, he was particularly close to his father, who led him early in life to an interest in natural phenomena.

In 1894 Prandtl entered the Technische Hochschule at Munich to study engineering. He graduated in 1898 and two years later completed his doctorate under the famous mechanics professor, August Föppl, who had been one of his undergraduate teachers. His thesis dealt with the lateral instability of beams in bending. Although the mechanics of solids was to become a secondary interest, it was an area in which Prandtl continued to contribute significantly. He discovered the well-known soap film analogy for the Saint Venant torsion problem in 1904 and did fundamental work in plastic deformation during the early 1920's.

Prandtl's interest in fluid flow began immediately after his graduation from Munich. He went to work in the Maschinenfabrik Augsburg-Nürnberg, where he was asked to improve a suction device for the removal of shavings. In the process of greatly improving the device, he came to recognize some basic weaknesses in the current understanding of fluid mechanics.

One weakness was the inability of existing fluid mechanics to explain why the moving fluid in a pipe would separate from the wall in a sharply divergent section instead of expanding to fill the pipe. In the course of the next three years Prandtl attacked this problem in a way that was to be characteristic of his later work. After accepting a professorship at the Hannover Technische Hochschule in 1901, he proceeded to ask what the missing element in the existing analyses of pipe flows might have been. By 1904 he had developed his celebrated paper on the flow of fluids with small viscosity. In it he showed that no matter how small the viscosity was, the fluid had to be stationary on the walls of the pipe. Thus the classical theory of inviscid fluids could never be employed without taking cognizance of the way in which a thin viscous region near the wall shaped the flow. An understanding of this region, the boundary layer, was to facilitate the subsequent explanation of lift and drag on airfoils, and aspects of almost all other aerodynamic behavior. Prandtl's insight thus led him to the large problem that lay behind a small one, and he set in motion a program of theoretical and experimental research that is still being worked out today.

By this time a new wind had begun to blow through the German system of higher education. The mathematician Felix Klein, feeling that the gulf between mathematics and technology was too wide, had established several technical institutes at Göttingen University. On Föppl's recommendation Klein gave Prandtl a chair at Göttingen and placed him in charge of the Institute for Technical Physics. Just after this move Prandtl's presentation of the boundary layer paper at the Third International Congress of Mathematicians at Heidelberg won high praise from Klein, who was quick to understand what his new man had accomplished.

At Göttingen, Prandtl had very good graduate students and access to the resources and interest of industry. He also was encouraged to pursue more theoretical lines of research than he had been at Hannover. During his first years there he made lasting contributions to the theory of supersonic flow. He combined Riemann's theories with Mach's *Schlieren* flow visualization apparatus to obtain the first explanation of the behavior of supersonic nozzle efflux. Later he was responsible for the first mathematical description of supersonic flow around slender bodies. He also was instrumental in developing the first German wind tunnel, which was completed at Göttingen in 1909.

Meanwhile, in the autumn of 1906, Prandtl's most notable student arrived in Göttingen. Theodore von Kármán sought Prandtl out to direct his research on the theory of nonelastic buckling. He was only six years Prandtl's junior; and their lives and pursuits touched many times between 1906 and their last meeting in 1945, when Kármán, a Hungarian Jew who had become an American citizen, returned to Germany with an army interrogation team.

In his autobiography Kármán gives a picture of Prandtl that clearly mingles affection with annoyance. Prandtl's life was, he tells us, "particularly full of overtones of naïveté." In 1909, for example, Prandtl decided that he really ought to marry; but he didn't know how to proceed. Finally he wrote to Mrs. Föppl, asking for the hand of one of her daughters. But which one? Prandtl had not specified. At a family conference the Föppls made the practical decision that he should marry their eldest daughter, Gertrude. He did and the marriage was apparently a happy one. Two daughters were born in 1914 and 1917.

Another facet of his naïveté lay in Prandtl's inclination to absorb himself totally in what interested him. The details of toys and magic tricks fascinated him to the exclusion of his surroundings. His greatness as a teacher did not include greatness as a lecturer because "he could not make a statement without qualifying it" and consequently was tedious. Nevertheless Prandtl was personable, gracious, and unassuming. He was an accomplished pianist with a good musical sense. His importance as a researcher was matched by an extraordinary ability to work fruitfully with his individual students.

Prandtl's aerodynamic work developed steadily from 1909 to the end of World War I. Between 1909 and 1912 he helped to establish test codes for fans. In 1914 he explained a puzzling, sudden drop of the drag coefficient for a sphere that occurred with increasing velocity. He did this by again recognizing the important phenomenon underlying a minor problem: the laminar-to-turbulent transition of the boundary layer on the body.

Prandtl's most significant contribution during this period was his work on airfoil theory. The lift force on wings was fairly well understood, and he turned to the explanation of drag. The boundary layer gave rise directly to skin friction which was much too small to account for wing drag. In 1911 and 1912 Kármán, stimulated by the experimental work going on in Prandtl's laboratory, did much to explain another component, profile drag. He described the so-called Kármán street of alternating vortices, parallel with an aerodynamic body, that must be pulled along behind it. Prandtl continued to work on a third contribution, induced drag. He had recognized that the presence of lift causes a trailing vortex to be induced in the shape of a long distorted horseshoe with its base at the airport where the flight began and its ends at the wing tips, which continually generate the vortex.

Prandtl's attempts to analyze this source of drag subsequently fell under the veil of wartime secrecy, and his descriptions of the effect finally emerged in restricted Göttingen publications in 1918 and 1919. By 1920 the idea reached a larger public and wrought sharp changes in the wing design and streamlining of airplanes. It led in general to more cleanly shaped wings, to higher aspect ratios, to today's swept-back wings, and to the use of streamlining fillets.

The elusive problem of describing turbulent flow yielded to Prandtl's and Kármán's competitive efforts in the mid-1920's. Kármán, who then was teaching at Aachen, discussed the structure of turbulent flows in 1924 but failed to produce a strategy for analyzing it. In 1926 Prandtl provided the conceptual device needed to make an analysis. This was the "mixing length," or average distance that a swirling fluid element would travel before it dissipated its motion. The idea resembled the notion of a mean free path in the kinetic theory of gases and was used in a somewhat similar way. Subsequent experiments by Prandtl and theoretical work by Kármán made it possible for Prandtl to present a summary paper on the subject in 1933 that is the basis for chapters on turbulence in today's textbooks.

During the 1930's and 1940's Prandtl, now an elder statesman of fluid mechanics, continued to contribute to the basic literature and technology, and reaped honors for his accomplishments. Nevertheless, his interrogation by the U.S. Army in 1945 found that the mainstream of wartime technology had more or less bypassed Prandtl and Göttingen. Hitler had shown greater interest in the rocketry at Peenemunde and the laboratory at Brunswick. The team, arriving in Göttingen from the slave labor camp at Nordhausen, found Prandtl complaining peevishly about bomb damage to his roof and asking how the Americans planned to support his ongoing work.

While the picture is one of a technician who felt little obligation to anyone's politics, it forms a consistent view of Prandtl, who, after all, made enormous contributions to his world as a technologist. He was then seventy-one and just turning his attention to meteorology, on which he published material as late as 1950.

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John H. Lienhard

PRATT, FREDERICK HAVEN (*b.* Worcester, Massachusetts, 19 July 1873; *d.* Wellesley Hills, Massachusetts, 11 July 1958), *physiology.*

During a long teaching career, Pratt's main researches were in heart and muscle physiology; his investigations into the phenomena of muscle fiber contraction are classics of their time.

The son of Frederick Sumner Pratt, a merchant descended from early Massachusetts settlers, and Sarah McKean Hilliard, Pratt entered Harvard after attending preparatory school in his native Worcester, receiving the A.B. in 1896 and the A.M. in 1898. In the latter year he reported on experiments he had been conducting for some time to determine the role of the veins of Thebesius and of the coronary veins in the nutrition of the heart, a problem to which he returned years later.

His training enabled Pratt to combine a keen interest in the theoretical aspects of physiological research, which he examined in relation to their historical antecedents, with an expertise in the use of apparatus in experimentation. After studying at the University of Göttingen and a stay at the Worcester Polytechnic Institute, he became assistant in physiology at Harvard in 1901. He graduated from Harvard Medical School in 1906. He taught physiology in Wellesley College's department of hygiene until 1912, when he was appointed professor of physiology at the University of Buffalo. In that year he married Margery Wilerd Davis; they had five children.

The first of Pratt's researches into skeletal muscle fiber contraction applying the "all-or-none" principle was published while he was head of the department of physiology in the medical school at Buffalo. From 1919 to 1920 he was an honorary fellow in biology at Clark University, and the next year he served as teaching fellow in physiology at Harvard. Named professor of physiology at Boston University in 1921, he remained there until he retired emeritus in 1942. Later he headed a firm supplying apparatus for physiological research. A member of the American Physiological Society and other scientific societies, he was interested in the work of the Marine Biological Laboratory at Woods Hole, Massachusetts, and the Bermuda Biology Station. He wrote several biographical studies and was especially intrigued by the biological concepts of Emanuel Swedenborg, finding them in many ways modern and in some respects anticipatory of certain of his own regarding cardiac nutrition.

The gradation of muscle activity had engaged investigators before Pratt, with his undergraduate assistant John P. Eisenberger, set out to devise a method of determining by direct observation the response of single muscle fibers to stimuli. After Henry Pickering Bowditch in 1871, studying cardiac muscle, had set forth the "all-or-none" principle, others had explored the further applicability of the rule that independent of its strength, a stimulus, if it elicited a