Poiseuille's Observations on Blood Flow Lead to a Law in Hydrodynamics

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In recent years advances in the biological sciences have been largely dependent on the application of the physical sciences. The departments of biochemistry and biophysics found in practically all colleges and universities today give evidence of the fund of knowledge that has already been obtained and is being obtained by the fruitful application of the methods of chemistry and physics to the biological field.[1]

The important role which the physical sciences have played in the progress of the biological sciences has eclipsed, more or less, the contributions which biologists have made to the physical sciences. Some of these contributions have become such an integral part of the physical sciences that their origin seems to have been forgotten. An outstanding example of such a contribution is that by Jean Léonard Marie Poiseuille[2] (1799–1869). About 100 years ago Poiseuille brought a fundamental law to that division of physics known as hydrodynamics—which is a branch of rheology, according to more recent terminology. This law resulted indirectly from his observations on the capillary circulation of certain animals. Most physicists, chemists and mathematicians associate the name of Poiseuille with the phenomenon of viscosity because the cgs absolute unit for the viscosity coefficient has been named the *poise* in his honor. Few know the story leading up to the discovery of the law which bears his name. This law had more fundamental significance than Poiseuille himself realized. It established an excellent experimental method for the measurement of the viscosity coefficients of liquids. The underlying principle of this method is in use today. Since Poiseuille's law was based entirely on experiment, it was purely empirical. However, the law can be obtained theoretically. Those who are familiar with only the theoretical development are generally surprised to learn that the law was originally determined experimentally—and still more surprised to know that Poiseuille got his idea from studying the character of the flow of blood in the capillaries of certain animals.[3]

Poiseuille was, at heart, a physicist. At the age of eighteen years he entered the École Polytechnique in Paris, where he received good training in physics and mathematics. When this school closed its doors, he entered the medical school. His thesis for the M.D. degree was a study of the strength of the aortic heart. After receiving his degree he became free teacher of medical physics. It is said that he always devoted some time out of each day to mathematics and physics.

The epoch-making experiments of Poiseuille which established the law bearing his name are published in a journal not readily accessible. However, Brillouin[4] has described them in considerable detail and Bingham[5(a)] has outlined them more briefly. The appendix of Bingham's book contains Poiseuille's original data. Recently Bingham[5(b)] has edited a monograph that contains a translation by Winslow H. Herschel

[1] One of the most recent interesting educational developments pertaining to the training of future biophysicists and biochemists is the establishment of a new type of department called *biological engineering* at the Massachusetts Institute of Technology; see K. T. Compton, "Possibilities in biological engineering," Ann. Int. Med. **12**, 867–875 (1938).

[2] J. L. M. Poiseuille: (*a*) "Recherches sur les causes du mouvement du sang dans les vaisseaux capillaires," Compt. rend. Acad. d. sc. **1**, 554–560 (1835); (*b*) "Recherches sur les causes du mouvement du sang dans les vaisseaux capillaires," Mém. prés. Acad. d. sc. de l'Inst. de France, Par. **7**, 105–175 (1841); (*c*) "Recherches expérimentales sur le mouvement des liquides dans les tubes de très petits diamètres," Compt. rend. Acad. d. sc. **11**, 961–967, 1041–1048 (1840); **12**, 112–115 (1841); **15**, 1167–1187 (1842); (*d*) "Experimentelle Untersuchungen über die Bewegung der Flüssigkeiten in Rohren von sehr kleinen Durchmessern" [Bericht einer aus den H. H. Arago, Babinet, Piobert und Regnault gebildeten Kommission über diese Abhandlung, Ann. de chim. et de Phys. **7**, (3) **7**, 50 (1843)], Ann. d. Phys. u. Chem. **58**, 424–448 (1843); (*e*) "Recherches expérimentales sur le mouvement des liquides dans les tubes de très petits diamètres," Paris, Mém. Savans Étrange **9**, 433–544 (1846).

[3] When one of the leading hydraulic engineers in our country—R. E. Horton—learned that I was reading the original publications of Poiseuille with the idea of publishing a note concerning them, he wrote: ". . . I hope I may induce you to say something that will tend to restore to Poiseuille the credit to which he is entitled."

[4] M. Brillouin, *Leçons sur la viscosité des liquides et des gaz* (Gauthier-Villers, Paris, 1907), Vol. II.

[5] E. C. Bingham: (*a*) *Fluidity and plasticity* (McGraw-Hill, 1922); (*b*) *Rheological memoirs* (Lancaster Press), vol. 1, No. 1.

of Poiseuille's epoch-making paper,[2(e)] "Recherches expérimentales sur le mouvement des liquides dans les tubes de très petits diamètres." Barr[6] gave a detailed description of Poiseuille's viscometer and paid a nice tribute to him when he wrote about his experimental work thus: "It forms one of the classics of experimental science and is frequently quoted as a model of careful analysis of sources of error and painstaking investigation of the effects of separate variables."

Poiseuille's experiments on the flow of liquids in glass tubes were so simple and the results so surprising that a committee was appointed to investigate the research. The experiments were repeated carefully and no error could be found. The experiments can be repeated today with the same results. Poiseuille made his experiments for the ages. What more can be said of an experimental investigator?

Poiseuille's results were surprising because the new law he derived was not in agreement with the laws of flow of liquids previously developed except for the law developed by Hagen[7] one year previously. Girard,[8] an outstanding physicist at the time, had found a more complex relation between volume flow, pressure and the dimensions of the tube. Navier,[9] and later Stokes,[10] developed a law for the flow of liquids in tubes from a purely theoretical point of view. Navier's equation did not agree with that of Poiseuille. The beauty of Poiseuille's experiments and their results was their simplicity. At this point I am prompted to introduce a quotation from a review by Swann[11] of Eve's biography of Lord Rutherford. In reference to the work of Rutherford the statement is made:

> Most worthy of all is the extreme simplicity and directness of his experimental methods. Some observers seem to grow happier as their apparatus becomes more complex.

Poiseuille's complete data are available for any one who wishes to study them. Many competent critics have done so. Knibbs's[12] paper on "The history, theory and determination of the viscosity of water by the efflux method" is an example of a way in which these data have been used.

It is seldom that any investigation can be regarded as final. Despite the fact that the unit for the viscosity coefficient is named the poise, Poiseuille himself did not introduce this coefficient into his formula. The constant factor in his law included this coefficient but it was not introduced explicitly until 1860 by Hagenbach[13] and also by Jacobson.[14] Navier, however, used this coefficient in his theoretical treatment although it was not definitely named. Today, other corrections and modifications are being made in Poiseuille's law according to the demands of the problem to which it is being applied. In a recent paper Hersey and Snyder[15] wrote:

> Departure of Eq. (3) from the usual form of Poiseuille's law should not, however, be taken to indicate any failure of Poiseuille's law in a physical sense. In

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[6] Guy Barr, *A monograph of viscometry* (Oxford Univ. Press, 1931).

[7] G. H. L. Hagen, "Ueber die Bewegung des Wassers in engen cylindrischen Röhren," Ann. d. Phys. u. Chem. **46**, 423–442 (1839).

[8] P. S. Girard: (*a*) "Mémoire sur le mouvement des fluides dans les tubes capillaires, et l'influence de la température sur ce mouvement," Paris, Mém. de l'Inst. 249–380 (1813–1815); (*b*) "Mémoire sur l'écoulement linéaire de diverses substances liquides par des tubes capillaires de verre," Paris, Mém. Acad. Sci. **1**, 187–259 (1816); (*c*) "Mémoire sur l'écoulement linéaire de diverses substances liquides par des tubes capillaires de verre," Ann. de chim. **4**, 146–164 (1817); (*d*) "Mémoire sur l'écoulement de l'éther et de quelques autres fluides par des tubes capillaires de verre," Paris, Mém. Acad. Sci. **1**, 260–274 (1816); Ann. de chim. **6**, 225–238, 334–336 (1817).

[9] C. L. M. H. Navier: (*a*) "Sur les lois des mouvements des fluides en ayant égard à l'adhésion des molécules," Ann. de chim. et phys. **19**, 244–260 (1821); (*b*) "Mémoire sur les lois du mouvement des fluides," Paris, Mém. Acad. Sci., **6**, 389–440 (1823); **9**, 311–378 (1830).

[10] G. G. Stokes: (*a*) "On some cases of fluid motion," Trans. Camb. Phil. Soc. **8**, 105–137 (1849); "On the theories of the internal friction of fluids in motion and of the equilibrium and motion of elastic solids," Trans. Camb. Phil. Soc. **8**, 287–319 (1849); (*b*) *Mathematical and physical papers* (Cambridge, 1880), vol. 1, p. 75.

[11] W. F. G. Swann, "The life and letters of Lord Rutherford," Science **91**, 46–48 (Jan. 12, 1940).

[12] G. H. Knibbs, "The history, theory and determination of the viscosity of water by the efflux method," N. S. Wales Roy. Soc. J. **29**, 77–146 (1895); "Note on recent determinations of the viscosity of water by the efflux method," N. S. Wales Roy. Soc. J. **30**, 186–193 (1897).

[13] Eduard Hagenbach, "Ueber die Bestimmung der Zähigkeit einer Flüssigkeit durch den Ausfluss aus Röhren," Ann. der Physik **109**, 385–426 (1860).

[14] Heinrich Jacobson, Arch. f. Anat., Physiol. H. Wissensch. Med.: "Zur Einleitung in die Hämodynamik," 305–328 (1861); "Beiträge zur Hämodynamik," 80–112 (1860); "Beiträge zur Hämodynamik," 683–702 (1862); "Ueber die Blutbewegung in den Venen," 224–242 (1867).

[15] M. D. Hersey and G. H. S. Snyder, "High-pressure capillary flow. Theory of nonuniform viscosity; illustrated by experimental data," J. Rheology **3**, 298–300 (1932). Eqs. (1) and (3), mentioned in the quotation, are equations that appear in the paper.

fact, the proof of Eq. (1) and hence of Eq. (3) is obtained by integrating the pressure drop along successive elements of the capillary, treating the viscosity as a constant in any one element and computing the flow through each element on the basis of Poiseuille's law.

It was the nature of the flow of blood in the capillary vessels of certain animals that challenged Poiseuille to begin the study of the laws governing the flow. Obviously, the way to begin such an investigation is to set up an artificial schema—an analog—whereby the supposed controlling factors may be studied separately. After developing his law, Poiseuille did not make a thorough investigation concerning its validity in the flow of blood. This problem was left to his followers.

Interestingly enough, physiologists have found that Poiseuille's law is not valid for the flow of blood. This is not surprising for several reasons, one being the nature of the liquid. Poiseuille's experiments were confined to homogeneous liquids flowing uniformly in small capillary glass tubes. Blood is a suspensoid and its viscosity is a function of the number and size of the corpuscular elements present. Poiseuille set out to place the flow of blood, as he observed it in capillaries, on a rational basis and he arrived at a deduction that does not apply rigorously to blood. However, this does not, in any way, detract from the contribution which he made to the science of hydrodynamics.

The experiments which stimulated Poiseuille to study the flow of water in glass capillary tubes are seldom mentioned. I have spent years in the measurement of blood flow and I was therefore keenly interested in the fact that the study of the circulation of the blood prompted Poiseuille's epoch-making experiments. For this reason his original papers on the flow of blood were consulted. Poiseuille's observations on blood were made as painstakingly and completely as his famous experiments on the flow of water.

From the time that Malpighi[16] discovered the capillaries to the time of Poiseuille, physiologists had observed the capillary circulation and had postulated hypotheses for the mechanism of movements as viewed through the microscope. Only one term, "globule," was used when referring to the various cells in the circulating blood. These globules could be seen to assume various velocities under apparently the same conditions. If one would focus the attention on any two globules, he might observe that they seemed to be moving along with the same velocity because the two remained the same distance apart. Suddenly the one ahead would appear to slow down and the second globule would approach it. At other times the one in the rear would slow down and thus the distance between them would increase. At times the globules would appear to be stationary. Most curious of all was the rotary motion of the globules. Some globules would be undergoing rotation alone, some would be only in translation and others would have both types of motion simultaneously.

These observations led physiologists to make the assumption that the globules had the power of spontaneous activity similar to infusoria. Such a hypothesis did not require a control by the heart. In fact, the flow of blood in the capillaries was considered to be independent of the action of the heart. Physiologists at that time accepted the fact that the heart controls the flow of blood in arteries and veins, but they postulated two activating agents for the flow in capillaries: (1) the change in caliber of the capillaries due to their contractile power—a sort of sucking force on the part of these capillaries (the latter is according to the diction of a century ago); (2) spontaneous activity of the globules themselves which controlled not only their own motion, but that of the blood as well. Haller,[17] an eminent physiologist of the eighteenth century, believed in an attraction of the globules for one another. Poiseuille limited most of his observations to the capillaries in the web of the frog's foot, in the tadpoles of the salamander and the frog and in the mesentery of the frog, salamander, young rats and young mice.

Before undertaking his studies on the move-

[16] M. Malpighi, *De pulmonibus* (1661).

[17] Albertus Haller: (*a*) *Deux mémoires sur le mouvement du sang, et sur les effets de la saignée; fondés sur des expériences faites sur des animaux* (Bousquet, Lausanne, 1756); (*b*) *A dissertation on the motion of the blood, and on the effects of bleeding, verified by experiments made on living animals. To which are added, observations on the heart, proving that irritability is the primary cause of its motion.* Tr. by a physician. (J. Whiston, London, 1757).

ments of the globules, Poiseuille performed experiments which proved clearly that the flow of blood in the capillaries is controlled by the heart. He placed ligatures on the femoral artery of the frog when observing the capillaries in the web of the foot. This caused a stoppage of the flow. When he removed the ligature, the flow again took place, the motion originating in the axial stream. After a thorough study of the effect of ligating the artery, Poiseuille proceeded to observe the effect of placing a ligature on the femoral vein. The flow decreased (after ligature of the vein) but took on a pulsatile movement. At first the amplitude of the vibrations was about five globules and later it was only two. These vibrations were always exactly synchronous with the rhythm of the heart and would cease as soon as a ligature was placed about the artery. When the ligature was removed from the artery, the rhythmic activity of the globules would promptly begin. Therefore, concluded Poiseuille, the oscillations of the globules were due to the action of the heart. Haller and Spallanzani,[18] two learned physiologists of the eighteenth century, had believed that the heart controlled the capillary circulation. Poiseuille's carefully performed experiments confirmed their belief and also proved beyond any question the cardiac control of the circulation of the blood in the capillaries. Poiseuille also considered the elasticity of the walls of the artery and recognized it as an important accessory to the heart in the control of the capillary circulation.

Next, Poiseuille turned his attention to a study of the character of the flow of blood in the capillaries with the hope that he would be able to explain the variable movements of the globules. Many previous observers had noticed a transparent layer between the wall of the capillary and the moving globules. Some said this layer was an integral part of the wall. Poiseuille proved that this layer was a part of the fluid in the lumen of the capillary by causing it to disappear after the application of ligatures on the venous side. The transparent layer would disappear on stoppage of the flow of blood. Girard had already demonstrated the existence of an immobile layer of liquid next to the wall of a tube when he was studying the flow of liquids in larger pipes. Poiseuille recognized the same phenomenon in these capillaries and found the immobile layer to be considerably thinner than that calculated by the physicist. Poiseuille found the thickness of the transparent layer to be from an eighth to about a tenth of the diameter of the vessel. This plasma or transparent layer became narrower as the speed of the globules became slower and finally disappeared entirely when the flow was zero. When the frog had been fasted, Poiseuille made the interesting observation that the blood contained a much larger number of small circular globules.

Poiseuille observed that the velocity of the globule depended on its distance from the center or the axis of the blood vessel—that its velocity parallel to the axis was greatest at the center and that it gradually decreased, becoming zero at the wall. This observation was not original with Poiseuille. Malpighi, Haller and Spallanzani had made it previously. However, Poiseuille interpreted these different velocities as indexes of the character of the flow of the blood. He considered the fluid to be divided into several concentric cylindrical layers, the central layer being a thin filament and the outermost layer (a cylinder concentric with this thin filament) the immobile one next to the wall. This type of flow is well known today and various aspects of it are characterized by the terms *viscous*, *steady*, *streamline* and *laminar*.

Knowing that this was the nature of the flow of blood in the capillaries, Poiseuille could easily explain the various movements of the globules. The globules slide along the vessel with the speed of that layer of fluid in which they happen to be located. If a globule is located in the axial layer, it moves with maximal speed. If it is pushed by its neighbors into the marginal layer, it either moves extremely slowly or comes to rest. If part of its volume is located in the immobile layer and part in the next layer, which is moving, it will undergo a motion of rotation. If it finds itself in intermediate layers of different speeds, the globule will undergo both rotation

[18] Lazaro Spallanzani, *Experiments upon the circulation of the blood throughout the vascular system; on languid circulation; on the motion of the blood, independent of the action of the heart; and on the pulsations of the arteries*. With notes, and a sketch of the literary life of the author, by J. Tourdes. Tr. into English, and illustrated with additional notes, by R. Hall. (J. Ridgway, London, 1801).

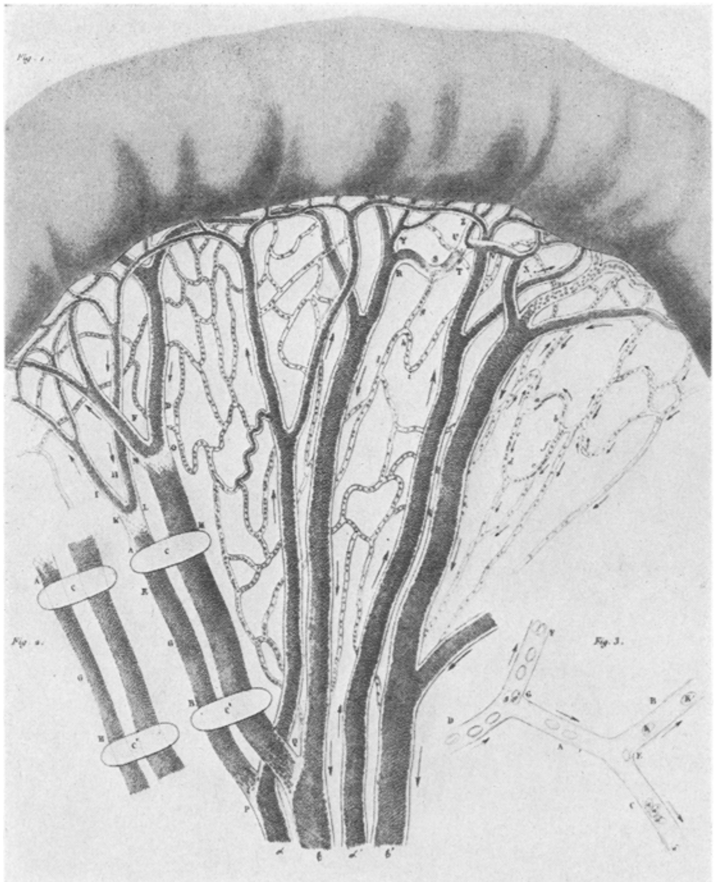

FIG. 1. A copy of Plate I from reference 2(*b*). Note the absence of the plasma layer in *Fig. 2* of this plate which is due to stoppage of flow by *C* and *C′*.

and translation. This last idea explains the whirling motion noted by earlier observers. It also explains how the distance between any two globules may sometimes increase and sometimes decrease. Under these conditions it is possible for several globules to come together, forming what is called an *agglomeration.* Such agglomerations could cause a blockage of flow which in turn would cause a reversal of flow (Figs. 1 and 2).

Poiseuille drew the following conclusions from his experiments: (1) the flow of blood in the capillaries is controlled by the heart; (2) the variable movement of the globules is not caused by some spontaneous mechanism within the globule itself but is due to the character of the flow of the liquid (the plasma).

Poiseuille's curiosity in regard to the movement of the blood in the capillaries was not yet satisfied. He wanted to know what effect various temperatures and pressures would have. Temperatures produced by placing the area including the capillaries in ice water caused either a complete cessation or a marked decrease of flow. If the water was warmed to about 40°C, the flow of blood attained a speed equal to that in the arteries. It is interesting to note that Poiseuille inferred a mechanism for the causation of disease from these observations, that is, that the cold season produces rheumatism.

Spallanzani had an ingenious apparatus for studying the effect of high pressures on certain physiologic processes but he did not disclose its nature; therefore, Poiseuille had to devise one of his own. Poiseuille's publication[2(b)] gave a complete description of the apparatus as well as an illustration. He subjected his animals to pressures ranging from 2 to 8 atmos as well as to subatmospheric pressures. He knew that newly born mice and rats could survive for a certain length of time without breathing, and this made it possible for him to observe the

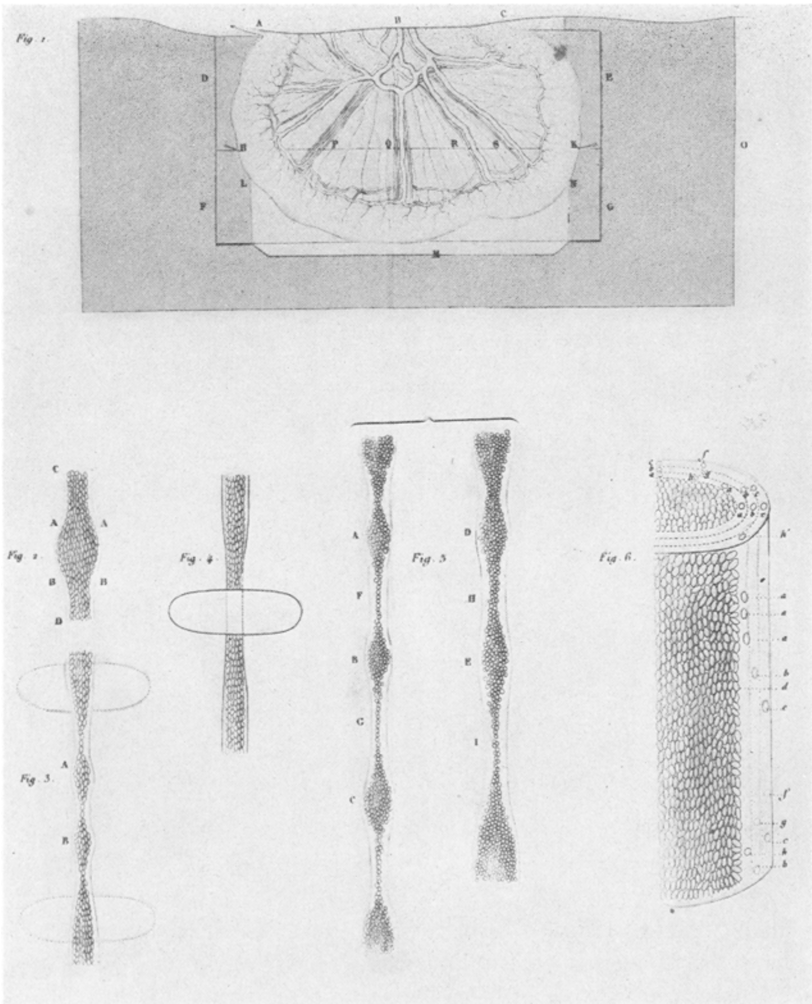

FIG. 2. A copy of Plate V from reference 2(*b*). Note the globules in the plasma layers in *Fig. 6* of this plate.

effect of a vacuum on the circulation. Poiseuille found that the circulation continued with the same rhythm when the animal was subjected to all these various pressures. The thickness of the transparent layer of plasma remained unaltered. These experiments show the incorrectness of the opinion of those physiologists who thought that circulation was impossible without atmospheric pressure.

Previous to Poiseuille's study of the flow of blood in capillaries he had made an extensive investigation of the blood pressure of dogs and horses. It was he who introduced the mercury manometer when measuring the pressure in arteries. He observed the oscillations of the column of mercury with each heart beat. He also observed the influence of the respiratory movements on the blood pressure. His observations extended to the measurement of venous pressures by means of a water manometer and the variations in venous pressure with respiration. He proved to his own satisfaction that respiratory movements aided the venous return.

With such an extensive study of the circulation of various animals, it is not surprising that Poiseuille became interested in hydrodynamics. In one of his publications he suggested that hydraulicians should use the circulation of animals as a means of learning about the movement of a liquid in tubes of small diameter and thus obtain data which could not be detected elsewhere. Apparently this idea grew on him until he decided to study the flow of liquids in very small capillary tubes himself in order to observe the effect of the various controlling factors separately. This was the work that made him immortal.[19]

ADDENDA

(1) Poiseuille's law may be found as the *Hagen-Poiseuille* or the *Poiseuille-Hagen* law in some textbooks or other references. Hagen, an engineer, developed the law and published it. Hagen's experiments were few whereas Poiseuille's experiments were numerous, and the fundamental experiments preliminary to those which established his law were published previous to the paper by Hagen. Bingham, Hatschek[20] and other critics have expressed the opinion that the law should have the one name of Poiseuille. The reason for the one name can be stated best by quoting Hatschek[21]: "Hagen's work, although practically a complete anticipation, has been overshadowed by that of Poiseuille, a short abstract of which appeared in the *Comptes Rendus* of 1842, his first paper being printed *in extenso* in 1846. No doubt this is largely due to the extraordinary completeness and elegance of the investigation, which still deserves careful study, and the fortunate accident that Poiseuille approached the problem as a physician interested in the circulation of blood in capillary vessels, and not as a hydraulic engineer; he accordingly used [glass] capillaries of very much smaller bore than any of his predecessors and had to deal with purely laminar flow."

Poiseuille was aware of Hagen's work. We find the following footnote in his paper which appeared in Annalen der Physik und Chemie[2(d)]: "Es ist dasselbe Mittel, dessen sich G. Hagen bei seinen Versuchen über die Bewegung des Wassers in zwar engen, aber nicht capillaren Röhren bediente."

(2) A law very similar to that of Poiseuille was developed experimentally for the purpose of calculating the flow of water through sand. The law is called *Darcy's law* after the man who developed it.[22] Some hydraulic engineers think that this law should be called Poiseuille's law because Darcy in his own paper recognized the fact that his law and that of Poiseuille were the same. Darcy thought it remarkable that he and Poiseuille arrived at the same law experimentally under such completely different circumstances.

[19] Biographies of Poiseuille: (*a*) Ann. de phys. **15–16**, 411–417 (1931); (*b*) P. L. B. Caffe, J. de conn. méd. prat. **37, 38**, 62–64, 1070–1071 (1870–1871); (*c*) M. Brillouin, J. Rheology **1**, 345–348 (1930).

[20] Emil Hatschek, *The viscosity of liquids* (Van Nostrand, 1928).

[21] Reference 20, p. 10.

[22] H. Darcy: (*a*) Compt. rend. Acad. d. sc. **38**, 407 (1854); (*b*) "Recherches expérimentales relatives au mouvement de l'eau dans les tuyaux," Paris, Mém. Savans Étrang. **15**, 141–403 (1858).

The Contribution of Physics to the College Curriculum

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IN an earlier paper[1] the writer has treated some of the general problems created for the teacher of any of the sciences by recent rapid changes, both in educational theory and in the new demands made by society on education at the college level. These new demands are becoming so insistent that curricular offerings which do not give them the consideration to which they are entitled are in danger of losing much of their opportunity to contribute to general education. The situation in which science instruction in the United States finds itself is, as Professor Taylor has recently pointed out very clearly,[2] a dangerous one, and it will be truly "the wisdom of self-preservation" to spend some thought on these problems before the trend away from the sciences develops into a mass movement which would strike the sciences altogether out of the general education curriculum. The present paper applies to physics the general considerations earlier developed for the sciences as a whole.[1]

THE TREND AWAY FROM PHYSICS

The attempt to remove the sciences from the curriculum or to deny them their full share in it starts from different, one can say opposite, considerations, according as one considers universities or secondary schools. A university is usually a loose union of faculties and departments with specialist interests, each of them trying to be more or less self-contained. The general physics course is preponderantly a service subject for the professional schools except to the extent that it is an introduction to physics itself as a profession. Medicine and the various branches of

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[1] Not yet published.

[2] L. W. Taylor, "Science in general education at the college level," Am. J. Phys. **8**, 41 (1940).