JULIUS ROBERT MAYER AND THE BLOOD'S CIRCULATION RATE

THE scientist appears most transcendent when he reaches a correct generalization by reasoning from instances which do not belong to the rule. Once a concept is suggested and formulated in the mind of the observer, the path which first guided may seem to be no longer of moment. The initial hypothesis then becomes a foolish incidental; it takes more than ordinary candor to admit the groundlessness of the first aberrant step. And the history of science is deficient in the details from which one might study the psychology of discovery.

One case in which the original wild guess has been recorded by its author occurred in the formulation of one of the greatest generalizations of science. The principle of the conservation of energy, the law which has unified many sciences into one, was undoubtedly first conceived by Julius Robert Mayer. But Mayer was not a physicist except by his fruits; he was a poor village physician, and his discovery resulted from apparently insignificant observations upon patients. A physician of mediocre ability may come to be classed in the best scientific society, when he pursues his thoughts as persistently as Mayer did.

Mayer was a native of Heilbronn, Germany, and received a routine training in medicine at the nearby University of Tübingen, and later at Munich. To see the world Mayer went in 1840, at the age of 26, as ship's surgeon on a Dutch freighter to Java. While bleeding patients in torrid Java he was struck with the unusually bright red color of the blood which came from the patients' veins. It was from this observation, by a chain of reasoning which involved assumptions now known to be physiologically incorrect, that Mayer arrived at a surprisingly adequate conception of the protean forces of nature.

Though ultimately Mayer became known as a theoretical physicist, primarily he was and remained a physician. His very method of mental procedure was that of the clinician to-day, a method which, juggle it as one will, always remains strikingly contrasted to that of the laboratory scientist, because of the infinite number of variables in a single clinical problem. Mayer reasoned from a few selected observations upon phenomena having many conditions not in common, to a generalization which then served as a guide for selecting other observations as they were met. His method in physical science was comparable to observing several cases of jaundice, demonstrating that they were accompanied by abnormal conditions in the liver, and thenceforth taking notice of those phenomena which by supposition bore information concerning the activities of the liver. Mayer spoke with authority in a circumscribed province of the sort in which the liver specialist holds sway; in other things he was more nearly a fool. Mayer's inexact methods were the forerunners of the precise work of Joule; while the latter's quantitative proofs immediately placed Mayer's reasoning and results out of date.

Mayer described the course of induction which led to his great generalization in the following words:[1]

In the summer of 1840, on the occasion of bleeding Europeans newly arrived in Java, I made the observation that the blood drawn from the vein of the arm possessed, almost without exception, a surprisingly bright red colour.

This phenomenon riveted my earnest attention. Starting from Lavoisier's theory, according to which animal heat is the result of a process of combustion, I regarded the twofold change of colour which the blood undergoes in the capillaries as a sensible sign—as the visible indication—of an oxidation going on in the blood. In order that the human body may be kept at a uniform temperature, the *development* of heat within it must bear a quantitative relation to the heat *which it loses*—a relation, that is, to the temperature of the surrounding medium; and hence both the production of heat and the process of oxidation, as well as the *difference in colour* of the *two kinds of blood*, must be on the whole less in the torrid zones than in colder regions.

In accordance with this theory, and having regard to the known physiological facts which bear upon the question, the blood must be regarded as a fermenting liquid undergoing slow combustion, whose most important function—that is, sustaining the process of combustion—is fulfilled without the constituents of the blood (with the exception, that is, of the products of decomposition) leaving the cavities of the blood-vessels or coming into such relation with the organs that an interchange of matter can take place. This may be thus stated in other words: by far the greater part of the assimilated food is burned in the cavities of the blood-vessels themselves, for the purpose of producing a physical effect, and a comparatively small quantity only serves the less important end of ultimately entering the substance of the organs themselves, so as to occasion growth and the renewal of the worn-out solid parts.

If hence it follows that a general balance must be struck in the organism between receipts and expenditure, or between work done and wear and tear, it is unmistakably one of the most important problems with which the physiologist has to deal, to make himself as thoroughly acquainted as it is possible for him to be with the budget of the object of his examination. The wear and tear consists in the amount of matter consumed; the work done is the evolution of heat. . . . The physiological theory of combustion starts from the fundamental proposition, that the quantity of heat which results from

[1] Mayer, J. R., 1851: "The Mechanical Equivalent of Heat." Transl. by J. C. Foster in "The Correlation and Conservation of Forces," edited by E. L. Youmans, New York, 1864, pages 324–325.

the combustion of a given substance is *invariable*. . . . Hence it follows, no less inevitably, that the heat produced mechanically by the organism must bear an invariable quantitative relation to the work expected in producing it.

Mayer's conclusion[2] was first published in 1842. Let us try to travel again over his course of reasoning, but with the enlightenment of present-day knowledge.

With the discovery of oxygen it was proven[3,4] that without oxygen there could be no combustion and that oxygen was used up in both respiration and in ordinary combustion. Therefore, reasoned Mayer, the amount of oxygen supplied must be a measure of the amount of combustion going on. This was nothing new, but Mayer was the first to whom a further implication became deeply significant, namely, that the amount of heat produced by respiration must be not only proportional to, but also quantitatively derived from, the amount of oxygen used up. Such a thought had apparently never impressed Lavoisier. Mayer next showed his physician's conception of the economy of the living body. Assuming that the redness of the blood is a semi-quantitative measure of its oxygen content, the unusual redness observed in a hot climate must represent a saving on the organism's part. If the chief end of oxygen utilization is the production of heat to maintain the body's temperature, then a saving of oxygen must mean that less heat is required for temperature maintenance. Eventually Mayer drew from these logical steps his epoch-making conclusions that an oxidative chemical reaction is a quantitative conversion of chemical energy into heat, and ultimately that all "forces" are quantitatively convertible into one another.

Now no one in Mayer's day, and least of all a physicist, could have found any fallacy in this correlation of physical and physiological facts. It has remained for the physiology of the subsequent century, and chiefly that of the last decade, to find any. It turns out that Mayer's reasoning was wrong in the very first step, in the inference "having regard to the known physiological facts" that the color of the blood in the veins is a measure of rate at which oxygen is being consumed in the part of the body which it drains. What physiologist of 1842 could have conceived of the velocity of the blood's flow as a highly variable quantity? The arteries were thought to carry the blood passively in every sense;[5] surely of all the tissues the circulatory vessels did their work regardless of conditions in the body. Or who would have supposed that the quantity of blood in the system might alter rapidly and reversibly?[6] Indeed the conception of the blood system as a constant delivery pumping plant has been overthrown only in the last twenty-five years.

Let us see what intricate and numerous facts have to be understood before one can describe fully the relation between the body's temperature and the rate of oxygen consumption by the tissues from which a given vein brings blood.

The great teacher of physiology, Carl Ludwig, carried out some of his earliest researches[7] upon the regulation of the blood's circulation. It seems none too dogmatic to say that William Harvey's[8] calculation of the amount of the heart's output had been the first and last contribution to the quantitative study of the blood's circulation up to Ludwig's time. Ludwig's work dealt chiefly with the blood supply to particular parts of the organism. It was, indeed, impossible to study the effects of various influences upon the local circulation until the circulation as a whole could be measured in a normal individual. This has been accomplished only recently.[9,10,11] Thanks to the importance of the problem, however, many measurements of total circulation rate, that is, of the heart's output of blood, have been made by many methods, and the effects of exercise and the like have been studied.[10,12,13] The influence of a

[2] Mayer, J. R., 1842: "Bemerkungen über die Kräfte der unbelebten Natur." *Ann. d. Chem.*, *42*, 233–240.

[3] Priestley, J., 1772: "Observations on Different Kinds of Air." *Phil. Trans.*, *62*, 147–252.

[4] Lavoisier, A. L., 1777: "Expériences sur la respiration des animaux et sur les changements qui arrivent à l'air en passant par leur poumon." *Mém. Acad. Sci.*, 1777, 185–194.

[5] Young, T., 1809: "On the Function of the Heart and Arteries." *Phil. Trans.*, 1809, 1–31.

[6] Barcroft, J., *et al.*, 1922: "On the Relation of External Temperature to Blood Volume." *Phil. Trans.*, *211* B, 455–464.

[7] Ludwig, C., 1847: "Beiträge zur Kenntniss des Einflusses der Respirations-bewegungen auf den Blutlauf im Aortensystem." *Arch. f. Physiol.*, 1847, 242–302.

[8] Harvey, W., 1628: "De motu cordis et sanguinis." Frankfort-am-Main. English transl. by R. Willis, London, 1847, chapter 9.

[9] Krogh, A., and Lindhard, J., 1912: "Measurements of the Blood Flow through the Lungs of Man." *Skand. Arch. Physiol.*, *27*, 100–125.

[10] Douglas, C. G., and Haldane, J. S., 1922: "The Regulation of the General Circulation Rate in Man." *Jour. Physiol.*, *56*, 69–100.

[11] Henderson, Y., and Haggard, H. W., 1925: "The Circulation and its Measurement." *Amer. Jour. Physiol.*, *73*, 193–253.

[12] Boothby, W. M., 1915: "A Determination of the Circulation Rate in Man at Rest and at Work. The Regulation of the Circulation." *Amer. Jour. Physiol.*, *38*, 383–417.

[13] Lindhard, J., 1915: "Ueber das Minutenvolum des Herzens bei Ruhe und bei Muskelarbeit." *Arch. gesam. Physiol.*, *161*, 233–383.

hot environment or of unusual internal heat production upon the total circulation rate has only just been investigated.[13, 14] We can say with certainty that the total circulation rate always increases, but only by a comparatively small amount, as a result of the exposure of the body to heat. When heating effects have become excessive, owever, there ultimately comes on a slowing of t e circulation, and it appears that "heat stroke" is a ailure of the supply of fresh blood in essential tissues.[15]

At the present day it can be realized that complete information regarding the total circulation rate can furnish only a part of what one needs to answer a problem such as Mayer had before him. By a dramatic observation Claude Bernard had discovered[16] in 1852 that arteries are under the control of nerves; that locally vessels may expand or contract when certain nerves are stimulated. Investigations of the local control of arterial caliber have brought to light a great variety of influence upon, and of resulting variations in, the flow of blood through individual arteries.[17, 18] And recently several investigators[19, 20, 21] have completed the demonstration that the capillaries and venules are highly changeable and are under an equal number of combinations of nervous and chemical influences.

It is precisely these local vascular changes in caliber, capacity and elasticity which have been found to be extremely responsive to temperature changes of the body and of the environment. And it can be demonstrated at last that temperature changes in body and environment normally influence the body in the same way, for it is the skin, in touch with both body and environment, which first detects the temperature changes, and initiates and regulates the responses of the circulatory system.[15]

14 Barcroft, J., and Marshall, E. K., Jr., 1923: "Note on the Effect of External Temperature on the Circulation in Man." *Jour. Physiol., 58,* 145–156.

15 Adolph, E. F., 1924: "The Effects of Exposure to High Temperatures upon the Circulation in Man." *Amer. Jour. Physiol., 67,* 573–588.

16 Bernard, C., 1852: "Sur les effects de la section de la portion céphalique du grand sympathique." C. R. Soc. Biol., *4,* 168–170.

17 Gaskell, W. H., 1880: "On the Tonicity of the Heart and Blood Vessels." *Jour. Physiol., 3,* 48–75.

18 Bayliss, W. M., 1923: "The Vaso-motor System." London.

19 Hooker, D. R., 1920: "The Functional Activity of the Capillaries and Venules." *Amer. Jour. Physiol., 54,* 30–54.

20 Parrisius, W., 1921: "Zur Frage der Contractilität der menschlichen Hautcapillaren." *Arch. gesam. Physiol., 191,* 217–233.

21 Krogh, A., 1922: "The Anatomy and Physiology of Capillaries." New Haven.

Studies[22, 23] of local temperature stimulation go to show that the rate of blood flow in the arms, the very parts of the body which were observed by Mayer, may be augmented or decreased many fold by warming the skin. The demonstration that the venous blood of the arm comes to have the same oxygen content as the arterial blood leaving the heart, when the arm is simply warmed in water for ten minutes at 45° C.,[24] is a refined repetition of Mayer's basic observation. Yet it must be recognized that the blood's color is not directly proportional to its oxygen content,[25] and that the color which the blood confers upon the skin is a very erroneous index of metabolic conditions.[26] The difference in interpreting the observation which Mayer grasped at, which eighty-five years have made, is this: we now know that the high oxygen content of venous blood under the influence of a warm environment is due entirely to the extreme rapidity of blood flow. The rate of oxygen consumption in the arm or by the body can be measured accurately, and it has been found with certainty[27, 28] that, if anything, slightly more oxygen is used at such a time than is used at ordinary temperatures. But the rate of flow becomes so rapid that each portion of blood loses an almost immeasurably small percentage of its oxygen content.[29] The body is not saving on the production of heat.

The true physiological explanation of what Mayer observed under conditions of high temperature seems to be that, although the metabolic rate and circula-

22 Hewlett, A. W., 1911: "The Effect of Room Temperature upon the Blood-flow in the Arm, with a Few Observations on the Effect of Fever." *Heart, 2,* 230–239.

23 Hewlett, A. W., *et al.*, 1911: "The Effect of Some Hydrotherapeutic Procedures on the Blood-flow in the Arm." *Arch. Internal Med., 8,* 591–608.

24 Goldschmidt, S., and Light, A. B., 1925: "A Method of obtaining from Veins Blood Similar to Arterial Blood in Gaseous Content." *Jour. Biol. Chem., 64,* 53–58.

25 Barcroft, J., 1914: "The Respiratory Function of the Blood." Cambridge.

26 Goldschmidt, S., and Light, A. B., 1925: "A Cyanosis, unrelated to Oxygen Unsaturation, produced by Increased Peripheral Venous Pressure." *Amer. Jour. Physiol.,* 73, 173–192.

27 Stewart, G. N., 1911: "Studies on the Circulation in Man. I. The Measurement of the Blood-flow in the Hands." *Heart, 3,* 33–75.

28 McConnell, W. J., and Yagloglou, C. P., 1925: "Basal Metabolism as affected by Atmospheric Conditions." *Arch. Internal Med., 36,* 382–396.

29 Goldschmidt, S., and Light, A. B., 1925: "The Effect of Local Temperature upon the Peripheral Circulation and Metabolism of Tissues as Revealed by the Gaseous Content of Venous Blood." *Amer. Jour. Physiol., 73,* 146–172.

tion rate increase 10 or 25 or 50 per cent. throughout the body, depending upon the degree of the temperature influence, the circulation rate *through the extremities* increases several hundred per cent., thus conveying heat to surfaces where it may be dissipated.[30] Under the majority of circumstances, and in Java, this is a provision for cooling the organism which is far more effective than that of which Mayer conceived.

There was in Mayer's day a physiological teaching which, had it been true, would have overthrown his reasoning still more thoroughly. This was the idea, which originated with Lavoisier,[31] that all or most of the body's oxidations occur in the lungs. It is probable that Mayer as a medical student had been taught this; whether he promptly forgot it or whether he was too wise to accept it, we can not discern. It is clear that if oxidations really occur in the lungs, then the color of the venous blood could tell nothing about the rate of combustion in the body as a whole. The view taken by Mayer, that combustion occurs chiefly or solely within the blood itself while in the capillaries, is no more correct in theory, and much less sanctioned by tradition.

To infer from the color of the blood in the skin the condition of the blood over the whole body was perhaps Mayer's biggest fallacy. But who does not reason just as "superficially" in the present year of enlightenment? Fallacies are not created by laziness, even in Mayer's case. In later life Mayer's mind gave way before the stupendous and intricate conceptions of the universe to which he was led. He was taken to an insane asylum, but later recovered equilibrium, and spent the rest of his days in the simpler occupation of cultivating the vine.

It must have been beyond Mayer's conception actually to measure the rate of blood flow through a vein, or the rate of oxygen consumption in a living arm, or even the oxygen saturation of venous blood. Yet to-day the solution of such a minor problem as the effect of temperature conditions upon the utilization of oxygen in the tissues drained by a given vein has just been begun; indeed, it is only now that the physiological value of a given atmospheric temperature can be accurately known in terms of physical measurements.[32] Scientists and non-scientists talk more about climate than about any other one topic; and the circulatory system is the portion of us whose relation to the weather ultimately matters most.

Mayer's contribution to the recognition of the principle of the conservation of energy was purely qualitative; he came to deal with energy in a cosmical way, a useful way which a thorough physicist like Joule could not permit himself to take. Shall we suppose that if Mayer had known the truth about the red color of febrile venous blood he would never have discovered the equivalence between chemical energy and heat?

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[30] Goldschmidt, S., and Light, A. B., 1925: "A Comparison of the Gaseous Content of Blood from Veins of the Forearm and the Dorsal Surface of the Hand as Indicative of Blood Flow and Metabolic Differences in These Parts." *Amer. Jour. Physiol., 73,* 127–145.

[31] *Loc. cit.*

[32] Houghton, F. C., and Yagloglou, C. P., 1924: "Cooling Effect on Human Beings produced by Various Air Velocities." *Jour. Amer. Soc. Heat-Vent. Engin., 30,* 169–184.

JOHN J. FLATHER

THE death of Professor John J. Flather of the University of Minnesota which occurred on Friday, May 14, 1926, at his home in Minneapolis, came as a surprise and a shock to his many friends. Although he had not been in the best of health for several years, his usual energy enabled him to perform his full duty as a teacher and as the administrative head of the department of mechanical engineering. Quite recently he has had trouble with his heart and just a day or two before his death his physician ordered a complete rest and cessation of all active work. Professor Flather was at the university up to the day before his death.

Professor Flather was born at Philadelphia, June 9, 1862. His father was English and his mother a native of Virginia. He was educated in private schools in Scotland, and the high school at Bridgeport, Conn., later attending Yale University where he graduated in 1883. He did graduate study at Cornell University and received the degree of Master of Mechanical Engineering in 1890. He also studied at the University of Edinburgh.

The early professional experience of Professor Flather includes a full apprenticeship in various machine shops in New England, journeyman experience as a toolmaker for the Yale & Towne Mfg. Co., designer and foreman for the Ansonia Electric Co., and superintendent of the Buffalo Steam Pump Co., and afterwards of the Hotchkiss Mfg. Co. of Bridgeport, Conn.

In 1888, he began his teaching work as instructor in mechanical engineering at Lehigh University, where he remained three years. From 1891 to 1898, he was professor of mechanical engineering at Purdue University. He came to the University of Minnesota in 1898 as professor of mechanical engineering and head of the department, which position he held until his death. He has taught practically all the subjects in the mechanical engineering curriculum at some time