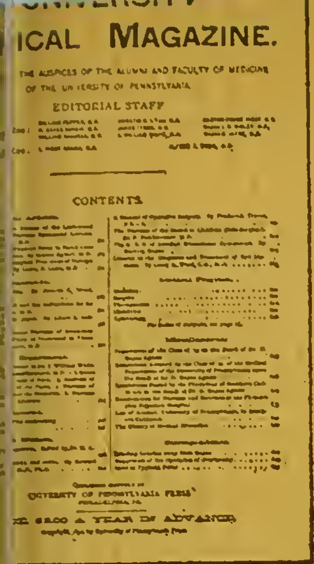
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THE

PHYSICAL AND PHYSIOLOGICAL BASIS OF COLOR.

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University of Pennsylvania.

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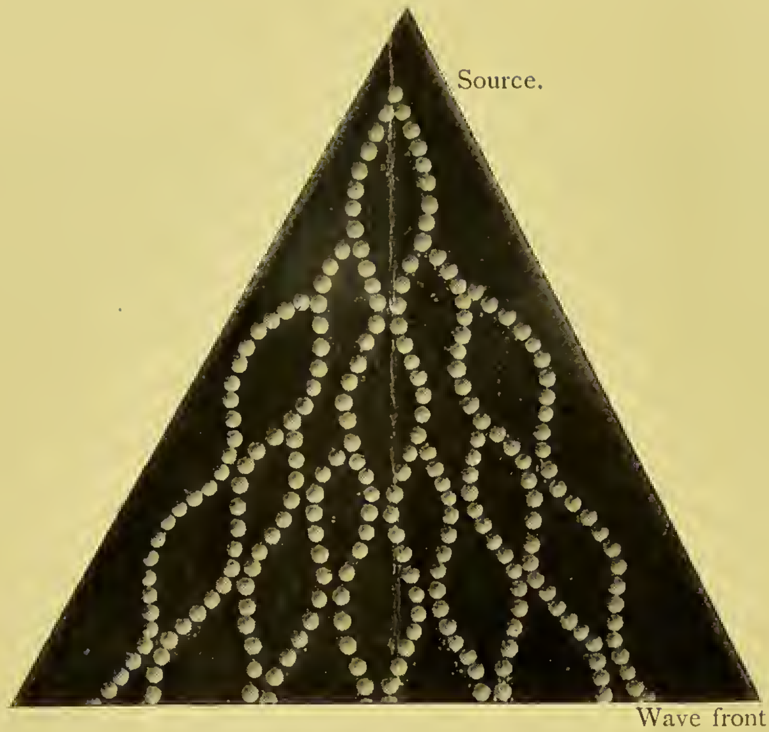
THE sensation of color is primitive and incapable of description. No one, for example, can describe the feeling which is produced in him by contemplating red or blue. It is entirely an attribute of the individual. It is not in any extensive degree a matter of contrast, such as is the case between heat and cold, or light and shade. Green does intensify red, and after a prolonged contemplation of either of these colors, there is a feeble awakening of its complementary, but neither weakens the other as heat and cold. On the contrary, each stands out with more boldness when placed in proximity with the other. What is true of red and green is also true of orange and blue, as well as yellow and violet. The decomposition of a beam of sunlight by means of refraction through a prism reveals to us an extended series of colors ranging from dark-red through yellow, orange, green, blue, indigo, into violet. The alteration in the direction of the various color-rays is greatest in the violet, and diminishes as we approach the red. As a result of this dispersion we perceive the colors successively, and therefore separately. If the colors are recombined by another prism, we then perceive them simultaneously, and their individuality is lost in the combined sensations which constitute white light. Our perception of a color is, therefore, dependent on an impression made upon our eyes by rays which correspond to a limited portion of the spectrum. The simultaneous perception of rays corresponding to two different portions of the spectrum may produce the sensation of white light without necessarily the remaining portions of the spectrum being included. It is evident that if the sum of all the color sensations results in the impression of white and the combination of two simultaneous color sensations produces the impression of white, whatever essential is produced in the first case must also be produced in the latter. In the human eye simultaneous impressions are easily produced, a luminous circle is easily made by a burning stick whirled around in the hand. A rapidly-rotating wheel with colors properly placed produces the sensation of white. The colored lights from two lanterns thrown upon a screen will produce white light if suitably arranged. We may with advantage consider first the physical construction of the luminous waves and then observe the organs which are fitted to receive them.

To understand the phenomena of light we must assume that light is a transmission of energy from a luminous source to our eyes. The force acting on the molecules of transparent matter held in equilibrium by mutual attraction and repulsion, forces them asunder on the one hand and crowds them together on the other, the elasticity of matter now reverses the relative conditions, and what was at first an expansion becomes a contraction. The course of this phase has been an area bounded by curved lines. There are three dimensions io consider: the length which corresponds to the course of the wave and the two directions at right angles to this and to each other. The single phase of such an undulation would, therefore, assume, we will say, the shape of an egg, or perhaps a prolate spheroid. As each phase is completed, four new undulations take the place of the primitive one, in accordance with the law that the intensity of light diminishes as the square of the distance. Whatever form we give to such an undulation must be equally the form of the contiguous ones, since the two factors are the mutual attraction and repulsion of the molecules of matter, set in vibration by the luminous force. Such a diagram is represented by Fig. 1, in which the apex of the triangle represents the origin of the light, and the base represents its expansion; within each of these undulations are arranged the various wave-lengths of the spectrum so as to reach the eye simultaneously and produce the sensation of white. This, of course, only represents what takes place in one plane. The imagination must arrange innumerable planes bisecting this one, in order to conceive of the expansion of the light-force in the three directions necessary to comprise volume. If we trace the expansion of a single undulation through several phases, we would, therefore, find the solid figure representing a cone. The most satisfactory evidence of the undulatory nature of light is afforded by the interference bands which present themselves under certain conditions. By means of a narrow slit controlled in the size of its aperture by making one of its sides movable and regulated by a screw, we have succeeded in obtaining vertical bands when the slit is held in a vertical position and directed towards the sky or the shade of a lamp. If a strong convex cylinder be held close to the eye with its axis horizontal and the slit be brought up until it is in the principal focus of the lens, we will have a numerous

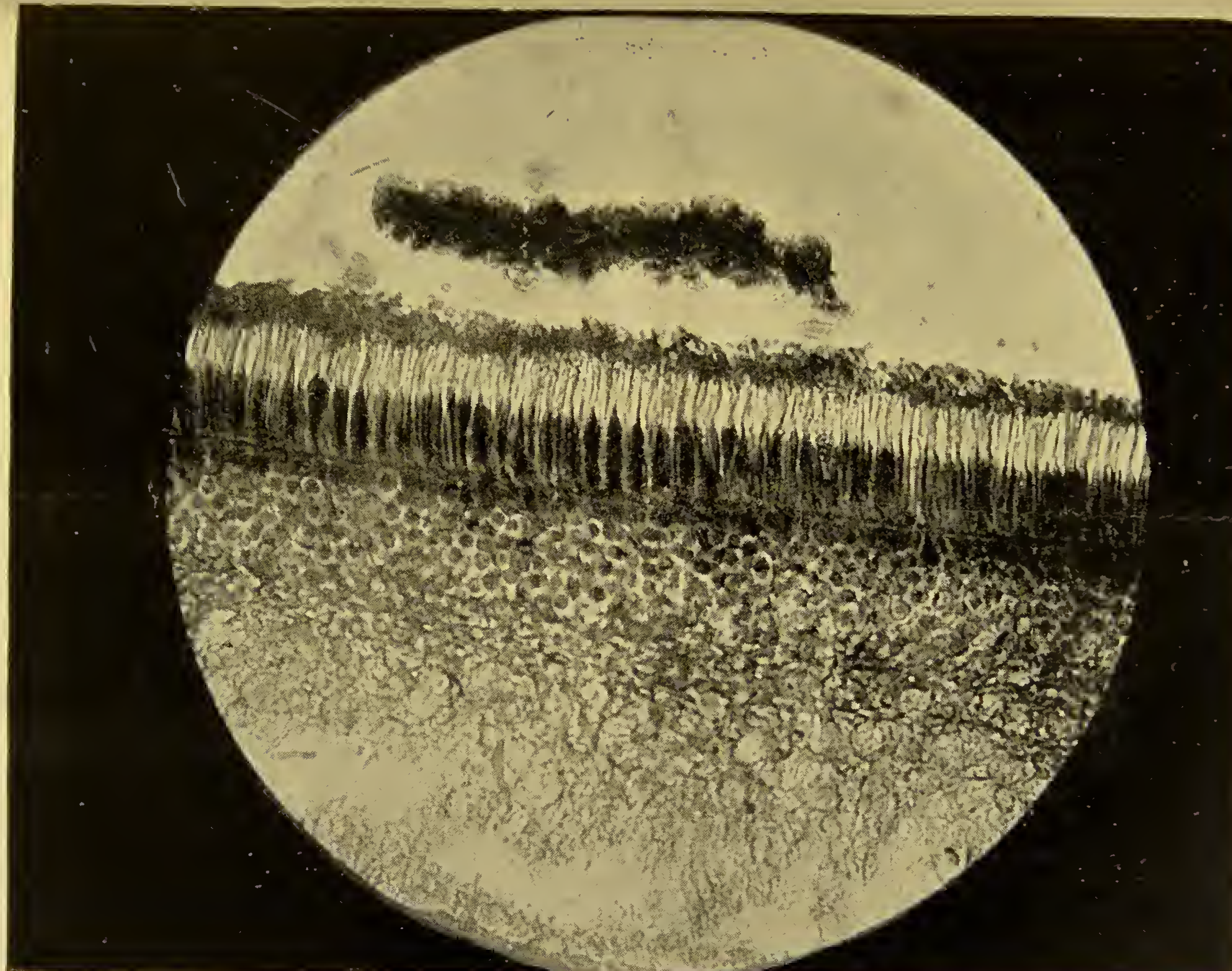
FIG. 1.



SCHEMATIC REPRESENTATION OF THE PROPAGATION OF LIGHT

FIG. 2.

PHOTOGRAPH OF THE INTERFERENCE BANDS SEEN THROUGH A SLIT.



Human Retina, Layer of Cones, × 600 Diameters.

series of sharp, horizontal lines, which are more numerous and also broader in proportion as the slit is made narrower. We have photographed in this way the bands, and present them in Fig. 2.

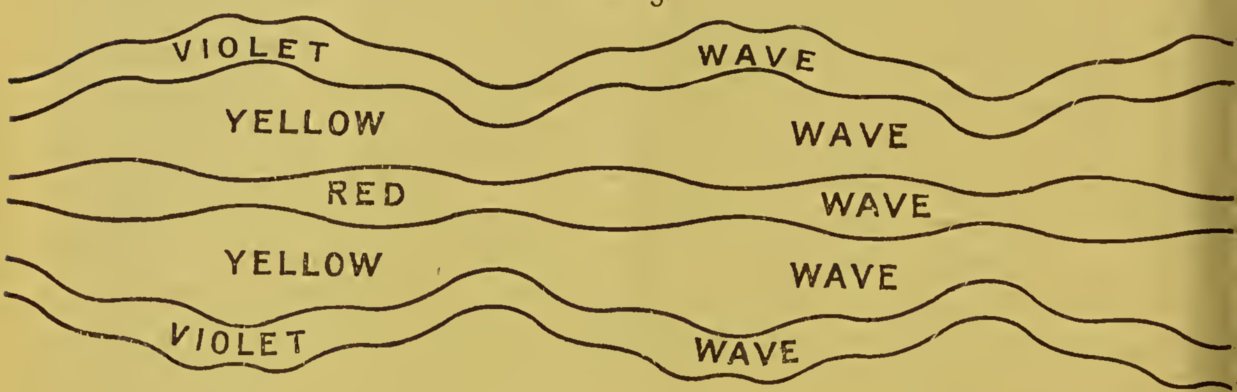
By means of a similar experiment with the diffraction gratings, it has been determined that the waves of the different portions of the spectrum neutralize each other, and produce bands that are dark, when two series of waves are made to intersect each other at a very slight angle. From this has been deduced the law that luminous waves travelling in the same direction, if they encounter each other in opposite phases or, which is the same, are following each other a half wave-length apart, extinguish each other and produce equilibrium in the ether or darkness to the eye. In this way the length of the wave of red light (line *A*) has been determined to be $\frac{1}{1315}$ of a millimetre. Yellow light (line *D*) $\frac{1}{1698}$ of a millimetre. Extreme violet (line *H*) $\frac{1}{2542}$ of a millimetre.[1] Reducing these ratios to whole numbers, which are approximately the same, the wave-lengths of these colors stand to each other in the proportion of 425 for red, 325 for yellow, 221 for violet, or let us say, 4 for the red, 3 for the yellow, 2 for the violet. The red waves are not quite multiples of the violet.

We will omit for simplicity's sake the other colors, and confine our attention to the arrangement in a single undulation of these unequal wave-lengths. A diagram representing these various waves must show in the same distance four — waves of violet light, three waves of yellow light, and two waves + of red light, such a diagram we show in Fig. 3, where the red waves are situated on the axis of undulation, the violet waves on the periphery, and the yellow intermediate. The number of vibrations of each corresponds to its length,—viz., two, three, four. A color wave whose times of vibration would be double, or any other even number of times, that of another would have its period of contraction occurring during the period of expansion of the other wave, and would thus produce an equilibrium or darkness. For this reason, beyond the extreme red and violet, are colors which extinguish each other, and this portion of the spectrum is invisible. The wave-lengths of the extreme visible colors are less than in a ratio of 1 : 2,—commencing at the violet and going towards the red. It is evident from this that each undulation has two phases, one of lateral expansion and one of contraction, the phase of one undulation must be the reciprocal of the phase of its adjacent undulation, or the phase of expansion of one undulation of the phase of contraction of the contiguous one. The same rule will apply in the arrangement of the vibrations within the undulation. If we were to assume that only three vibrations occurred in each undulation, then if we trace the inner-

[1] Lommel, Nature of Light.

most and the outermost we have also traced the intermediate. The ether waves of the inner and outer vibration would necessarily give rise to the wave of the intermediate vibration. Let us increase in imagination the number of vibrations to seven, to correspond with the usual division of the spectrum, then if we have numbers one and three of the series, number two will also be present. As a matter of fact, if

Fig. 3.



we have one and three, red and yellow, for example, we see number two, orange. To understand this we must take one color alone, say red. Each undulation will, therefore, have at first only the vibrations of the red waves, which pass through the centre. As the periods of expansion and contraction of the molecules occur, the surrounding molecules are alternately drawn towards the axis of the undulation and repelled from it, producing secondary vibrations in all the molecules of the undulation. The vibrations of the red waves would thus produce orange or yellow. The defective eye often sees red as yellow or orange; notably in perimetry when the red test object is held in the periphery. The so-called complementary colors are capable of producing white light. By observing the ratio of their vibrations we find that they are as 2 to 3. We may say, therefore, that light waves arranged around an axis with periods of vibration in the ratio of 2 to 3 produce a complete undulation. When the red light is withdrawn, and white light is substituted, the effect is green light and not white. Green must, therefore, be the mean effect of the residual vibrations of an undulation after the withdrawal of red, that is, yellow and blue waves are vibrating on either side of it. This is not only a subjective phenomenon, it is also apparent in what are known as colored shadows, where a red light intercepted by an opaque object gives rise to a green shadow, a blue light in the same way to an orange, and a violet to a yellow. In these cases the resultant effect would be a vibration of the molecules of ether of a definite number of times in each undulation, precisely similar to what would be produced by a green light. Borrowing a phrase from Keppler's third law, we might say that the times of the vibrations within an undulation are proportional to their distance from the axis.

All bodies vibrate in some measure, the rapidity of vibration is proportional to the length, density, and thickness of the body. If the variation in bodies is only in one of these elements, we may say that the rate of vibrations varies accordingly ; supposing the density and thickness to be constant, the vibrations would vary in proportion to the length. That this is so every one can prove by observing the increase in pitch in a violin, as the vibrating string is made shorter by the finger. In the apparatus of vision we would therefore look for some modifications of the percipient elements which would correspond to the rapidity of the vibrations. For blue waves we would expect shorter elements, or else shorter and thicker ; for red we would look for longer elements and thinner ones. As a matter of fact, the color red is perceived the most acutely of all, especially at a long distance. We would, therefore, expect to find the longest percipient elements in the macula lutea. We also know by experience that the color blue is visible in the periphery to a greater extent than any other. We would, therefore, expect to find in the periphery shorter or broader elements than in the macula lutea, Both these conditions may be obtained from the investigations of anatomists who have explored this portion of the human body. We would simply call attention to the first photo-micrograph of the cones accompanying a previous paper in this journal[1] which exhibits a variation between the smallest and the longest in the proportion of 1 to 2, which is precisely that of the violet and red waves. The portion of the section photographed was very near to the region of the macula lutea. We ought to find more long cones than short ones, as red is perceived so much better in central vision than blue. The cones are nearly all so long that we had difficulty in finding their terminal loops which were hidden in the pigment layer, one or two, however, can be made out.

Color perception would thus be determined by the structure of the retinal cones, possessing a range in length equal to the relative vibrations of the red and violet. A defect in the development of the retina which consisted in the absence of long cones would thus produce color-blindness for red. This was suggested to me by Dr. William F. Norris in the discussion of the previous paper on the anatomy of the retina. This point may be verified by some fortunate investigator who obtains an eye for examination known to have been color-blind for red during life. Color-blindness for red is a common one, and it is easily

[1] Norris and Wallace: A Contribution to the Anatomy of the Human Retina, etc.—UNIVERSITY MEDICAL MAGAZINE, March, 1894.

seen that long cones might be entirely absent from an eye; middle-sized cones could hardly fail to be present if there were already long and short ones, although short ones might be absent with the existence of long and middle-sized ones. We should therefore have two forms of color-blindness easy of demonstration,—namely, violet-blindness and red-blindness. Violet-blindness is rare. We can also have another condition,—namely, partial or complete absence of both extremes of sizes and a disproportionate number of the intermediate sizes. We think this condition can explain the phenomena of green-blindness in this way. The color sense is normally composed of three elements, red, yellow, and blue, all other colors are mixtures and can be resolved by the eye into two primaries. While each portion of the spectrum has a definite period of vibration, and therefore should produce an entirely distinct sensation, in point of fact, every wave-length is resolved by the eye into a simple or a mixed color sensation; an admixture of the third primary will extinguish part or all of the colors in the intense sensation which we call white, and which is due to the vibration of all the cones. In the case supposed, the extreme long and extreme short cones are diminished in number or entirely absent. Green, which produces a mixed sensation of yellow and blue, would thus excite all the intermediate cones and the resultant would be white of more or less intensity. To a green-blind person, green appears as a dirty white or gray. Although he can distinguish yellow or blue separately. But so does violet, and the two colors are confounded. The explanation of the violet appearing gray is very simple. The short cones being absent, violet produces no effect and is dark, the small amount of white light reflected from it moderates this into a gray, or a little mixture of green with the violet would add a little white, just as a little violet in green would add a little shadow to the white. The absence of the extreme long cones explains similarly the blindness for red, and the impurity of the red affords the explanation of the gray or dirty tint that it possesses. The color-blind patient for red thus sees in violet, the mixed color, only the blue. We thus see in our range of color perception the limits marked by red and blue, and as we approach a complete octave we find the sense of red becoming slightly excited to be entirely extinguished at either end of the spectrum, when the wave-lengths have become even multiples of each other. Although the ultra violet end may be extended if we shut off the red.

In conclusion, we desire to summarize these various portions of our subject as follows: The seat of the perception of red is in the longest cones, when these are not present red-blindness occurs. The seat of yellow perception is in cones shorter than the red. These are never absent, and no such a phenomenon as yellow-blindness exists.

The seat of blue perception is in the cones of smaller but not the smallest size. Blue-blindness is likewise unknown. Color-blindness is thus limited to two varieties,—first, red-blindness, in which there are no long cones to respond to the vibrations of the red waves; and, second, green-blindness, in which both long and short cones are absent, and the remaining elements are those which excite the sense of blue and yellow; if both are excited by green light, all the elements are thus thrown into vibration and the effect is white light. An objection to this theory will be that every portion of the spectrum emits rays which have a different period of vibration, and thousands of such various wave-lengths exist, but we have not thousands of different color sensations. We think there are in the retina a numerous series of cones, varying in their length to vibrate with the varying lengths of the ether waves; and just as a wave of monochromatic light will agitate the molecules on either side of it into vibration, so the various cones produce vibrations in those surrounding them until vibrations are aroused in those cones which awaken the primary color sensation; a mixed color sensation would thus originate in a wave of definite length, say green, but extending to either side would awaken both yellow and blue. If the retina possessed no cones corresponding to a particular wave of the spectrum, such a color would produce no effect, because no cone of proper length could start the vibrations. In this way we have red-blindness, caused by absence of the long cones, and violet-blindness, by absence of the short cones; green-blindness, which is caused by the absence of both long and short cones, contains also violet-blindness, either partial or complete, according to whether the long and short cones are partially or completely absent. The unequal distortion of the spectrum has caused green to be selected as the middle point, but in relative wave lengths, yellow occupies the middle between red and violet.