Philosophical Magazine Series 3

ISSN: 1941-5966 (Print) 1941-5974 (Online) Journal homepage: http://www.tandfonline.com/loi/tphm14

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To cite this article: Sir John F.W. Herschel K.H. (1833) LXIII. On the absorption of light by coloured media, viewed in connexion with the undulatory theory , Philosophical Magazine Series 3, 3:18, 401-412, DOI: 10.1080/14786443308648217

To link to this article: http://dx.doi.org/10.1080/14786443308648217

Published online: 01 Jun 2009.

THE
LONDON AND EDINBURGH
PHILOSOPHICAL MAGAZINE
AND
JOURNAL OF SCIENCE.

[THIRD SERIES.]

DECEMBER 1833.

LXIII. *On the Absorption of Light by Coloured Media, viewed in connexion with the Undulatory Theory.* *By Sir* JOHN F. W. HERSCHEL, *K.H.**

THE absorption of light by coloured media is a branch of physical optics which has only since a comparatively recent epoch been studied with that degree of attention which its importance merits. The speculations of Newton on the colours of natural bodies, however ingenious and elegant, can hardly, in the present state of our knowledge, be regarded as more than a premature generalization; and they have had the natural effect of such generalizations, when specious in themselves and supported by a weight of authority admitting for the time of no appeal, in repressing curiosity, by rendering further inquiry apparently superfluous, and turning attention into unproductive channels. I have shown, I think satisfactorily, however, in my Essay on Light, that the applicability of the analogy of the colours of thin plates to those of natural bodies is limited to a comparatively narrow range, while the phænomena of absorption, to which I consider the great majority of natural colours to be referrible, have always appeared to me to constitute a branch of photology *sui generis* to be studied in itself by the way of inductive inquiry, and by constant reference to facts as nature offers them.

The most remarkable feature in this class of facts consists in the unequal absorbability of the several prismatic rays, and the total abandonment of anything like regularity of progress

* Communicated by the Author. The substance of this paper was read before the Section of Physics of the British Association, at Cambridge.

in this respect as we proceed from one end of the spectrum to the other. When we contemplate the subject in this point of view, all idea of regular functional gradation is at an end. We seem to lose sight of the great law of continuity, and to find ourselves involved among desultory and seemingly capricious relations, quite unlike any which occur in other branches of optical science. It is, perhaps, as much owing to this as to anything, that the phænomena of absorption, in some recently published speculations, and in the view which Mr. Whewell has taken in his Report of the progress and actual condition of this department of natural philosophy, read to this Meeting, have been characterized as peculiarly difficult to reconcile with the undulatory theory of light. In so far as I have above described the phænomena in appropriate terms, it will be evident that a certain difficulty must attach to their reduction under the dominion of *any* theory, however competent, ultimately, to render a true account of them. Where such evidence of complication and suddenness of transition subsists on the face of any large assemblage of facts, we are not to expect that the mere mention of a few general propositions, like cabalistic words, shall all at once dissipate the complication, and render the whole plain and intelligible. If we represent the total intensity of light, in any point of a partially absorbed spectrum, by the ordinate of a curve whose abscissa indicates the place of the ray in order of refrangibility, it will be evident, from the enormous number of maxima and minima it admits, and from the sudden starts and frequent annihilations of its value through considerable amplitudes of its abscissa, that its equation, if reducible at all to analytical expression, must be of a singular and complex nature, and must at all events involve a great number of arbitrary constants dependent on the relation of the medium to light, as well as transcendents of a high and intricate order. We must not, therefore, set it down to the fault of either of the two rival theories if we do not at once perceive how such phænomena are to be reconciled to the one or to the other, but rather endeavour to satisfy ourselves whether there be, in the first instance, anything in the phænomena, generally considered, repugnant either to sound dynamical principles, or to the notions which those theories respectively involve as fundamental features.

Now, as regards only the general fact of the obstruction and ultimate extinction of light in its passage through gross media, if we compare the corpuscular and undulatory theories, we shall find that the former appeals to our ignorance, the latter to our knowledge, for its explanation of the absorptive phænomena. In attempting to explain the extinction of light, on the corpuscular doctrine, we have to account for the light so extinguished as a material body, which we must not suppose annihilated. It may, however, be transformed; and among the imponderable agents, heat, electricity, &c., it may be that we are to search for the light which has become thus comparatively stagnant. The heating power of the solar rays gives a *primâ facie* plausibility to the idea of a transformation of light into heat by absorption. But when we come to examine the matter more nearly, we find it encumbered on all sides with difficulties. How is it, for instance, that the most luminous rays are not the most calorific, but that, on the contrary, the calorific energy accompanies, in its greatest intensity, rays which possess comparatively feeble illuminating powers? These and other questions of similar nature may perhaps admit of answer in a more advanced stage of our knowledge; but at present there is none obvious. It is not without reason, therefore, that the question "What becomes of light?" which appears to have been agitated among the photologists of the last century, has been regarded as one of considerable importance as well as obscurity, by the corpuscular philosophers.

On the other hand, the answer to this question afforded by the undulatory theory of light is simple and distinct. The question "What becomes of light?" merges in the more general one, "What becomes of motion?" And the answer, on dynamical principles, is, that it continues for ever. No motion is, strictly speaking, annihilated; but it may be divided, and the divided parts made to oppose and, *in effect*, destroy each other. A body struck, however perfectly elastic. vibrates for a time, and then appears to sink into its original repose. But this apparent rest (even abstracting from the inquiry that part of the motion which may be conveyed away by the ambient air,) is nothing else than a state of subdivided and mutually destroying motion, in which every molecule continues to be agitated by an indefinite multitude of internally reflected waves, propagated through it in every possible direction, from every point in its surface on which they successively impinge. The superposition of such waves will, it is easily seen, at length operate their mutual destruction, which will be the more complete, the more irregular the figure of the body and the greater the number of internal reflections.

In the case of a body perfectly elastic and of a perfectly regular figure, the internal reflection of a wave once propagated within it in some particular direction might go on for ever without producing mutual destruction; and in sonorous bodies of a highly elastic nature we do in fact perceive it to continue for a very long time. But the least deviation from *perfect elasticity* resolves our conception of the vibrating mass into that of a multitude of inharmonious systems communicating with each other. At every transfer of an undulation from one such system into that adjacent, a partial echo is produced. The unity of the propagated wave is thus broken up, and a portion of it becomes scattered through the interior of the body in dispersed undulations from each such system, as from a centre of divergence. In consequence of the continual repetition of this process, after a greater or less number of passages to and fro of the original wave across the body, (however perfect we may suppose the reflections from its surface to be,) it becomes frittered away to an insensible amplitude, and resolved into innumerable others; crossing, recrossing, and mutually destroying each other, while each of the secondary waves so produced is in its turn undergoing the same process of disruption and degradation.

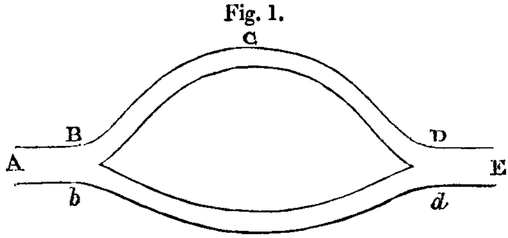
In this account of the destruction of motion, I have purposely supposed the body set in vibration to be insulated from communication with any other. In the case of a perfectly or highly elastic body struck in air, it will vibrate so long that a great part of its motion is actually carried off in sonorous tremors communicated to the air. But in the case of an inelastic or imperfectly elastic body, the internal process above described goes on with such excessive rapidity, as to allow of very few, and those rapidly degrading, impulses to be communicated from its surface to the air.

In my Essay on Sound, I have explained, on this principle of internal reflection and continual subdivision, in a medium consisting of loosely aggregated earth intermixed with much air, the hollow sounds which are often attributed to the reverberation of subterranean cavities, and in particular the celebrated instance of this kind of sound heard at the Solfaterra near Pozzuoli. The dull and ill-defined sound thus produced from a succession of partial echoes is there assimilated to the nebulous light which illuminates a milky medium when a strong beam is intromitted. If we suppose, now, such a mass of materials insulated from communication with the external air by some *sound-tight* envelope, these partial echoes, when they reach the surface in any direction, will be all sent back again as so many fresh impulses, till at length it will become impossible to assign a point within the mass which will not be agitated at one and the same moment by undulations traversing it in every possible phase and direction. Now the state of a molecule, under the influence of an infinite number of contradictory impulses thus superposed, is identical with a state of rest.

The only difficulty, then, which remains in the application of the undulatory theory to the absorptive phænomena, is to conceive how a medium (*i. e.* a combination of æthereal and gross * molecules) can be constituted so as to be transparent, or freely permeable to one ray or system of undulations, and opake, or difficultly permeable to another, differing but little in frequency. Now it is sufficient for our present purpose if, without pretending to analyse the actual structure of any optical medium, we can indicate structures and combinations in which air, in lieu of the æther, is the undulating medium, and which shall be either incapable of transmitting a musical sound of a given pitch, or shall transmit it much less readily than sounds of any other pitch, even those nearly adjacent to it. For that which experiment, or theory so well grounded as to be equally convincing with experiment, shows to be possible in the case of musical sounds, will hardly be denied to have its analogue or representative among the phænomena of colour, when referred to the vibrations of an æther.

An example of an acoustic combination, or compound vibrating system, incapable of transmitting a musical sound of a given pitch, is furnished by the pipe A E, which, after proceeding singly a certain length A B, at B branches off into two equal

Fig. 1.



and symmetrically disposed pipes B C and *b c*, which reunite again at D *d*, and there again constitute a single pipe D E, whose direction shall (like A B) bisect the angle between the branches. The branches, however, are of unequal length, the one B C D being longer than the other, by a quantity equal to half the length of the undulation or pulse of the musical note in question. It is evident, then, that if that note be sounded at A, each pulse will subdivide itself at B *b*, and the divided portions will run on along the two branches with equal intensities till they reunite at D *d*. They will arrive there, how-

* By *gross* molecules, or gross bodies, I understand the *ponderable* constituents of the material world, whether solid, liquid, or gaseous; using the term in contradistinction to æthereal, which has reference to the luminiferous æther.

ever, in opposite phases, and will therefore destroy each other at their point of reunion, and in every point of their subsequent course along the pipe D E; so that on applying the ear at E no sound should be heard, or at best a very feeble one, arising from some slight inequality in the intensities wherewith the undulations arrive by the longer and shorter pipe,—a difference which may be made to disappear, by giving the longer a trifle larger area for its section*.

Suppose now that the pipe instead of being cylindrical were square, and that the whole surface of one side of a chamber were occupied with the orifices A of such pipes, leaving only such intervals as might be necessary to give room for their due support, and for their subdivision according to the condition above explained; and suppose, further, that the other ends (E) of all the reunited pipes opened out, in like manner, into another chamber, at some considerable distance from the first, and separated from it by masonry or some material, filling in all the intervals between the pipes, so as to be completely impervious to sound. Things being so disposed, let the whole scale be sounded, or a concert of music performed in the first chamber, then will every note, except that one to which the pipes are thus rendered impervious, be transmitted. The scale, therefore, so transmitted, will be deficient by that note, which has been, to use the language of photologists, *absorbed* in its passage. If several such chambers were disposed in succession, communicating by compound pipes, rendered impervious (or *un*tuned, as we may term it,) to so many different notes, all these would be wanting in the scale on its arrival in the last chamber; thus imitating a spectrum in which several rays have been absorbed in their passage through a coloured medium.

In my Essay on Light, Art. 505, I have suggested, as a possible origin of the fixed lines in the solar spectrum, and (*pari ratione*) of the deficient or less bright spaces in the spectra of various flames, that the same indisposition in the molecules of an absorbent body to permit the passage of a particular coloured ray *through* them, may constitute an obstacle, *in limine*, to the production of that ray *from* them. The following easy experiment will explain my meaning. Take two

* I ought to observe, that I have not *made* the experiment described in the text, nor am I aware that it has ever been made; but it is easy to see that it ought to succeed, and would furnish an apt enough illustration of the principle of interference. Instead of a pipe, inclosing air, a canal of water might be used, in which waves of a certain breadth, excited by some mechanical contrivance at one end, would not be propagated beyond the point of reunion, D, of the two canals into which the main channel, A B, was divided.

tuning forks of the same pitch, and heating the ends of them, fasten with sealing-wax, on one of them one, and on the other two, disks of card, (all equal in size,) on the *inner* surfaces, having the plane of the card perpendicular to that of a section of the fork through the axes of both its branches. The cards on that fork which has two, should have their surfaces about a tenth of an inch asunder, and their centres just opposite; and the other fork should be brought into unison with it by loading its undisked branch with additional wax, equal in weight to the disk and wax on the other. Now strike the forks, and a remarkable difference will be perceived in the intensity of their sounds. The fork with one disk will utter a clear and loud sound, while that of the other will be dull and stifled, and hardly audible, unless held close to the ear. The reason of this difference is that the opposite branches of the fork are always in opposite states of motion, and that in consequence the air is agitated by either the two branches vibrating freely, or by both loaded with equal disks, with nearly equal and opposite impulses; whereas in the case of a fork furnished with only one disk, a greater command of the ambient medium is given to the branch carrying it, and a much larger portion of uncounteracted motion is propagated into the air. Here then we have a case in which a vibrating system in full activity is rendered, by a peculiarity of structure, incapable of sending forth its undulations with effect into the surrounding medium; while the very same mass of matter, *vibrating with the same intensity*, but more favourably disposed as to the arrangement of its parts, labours under no such disability.

The disked tuning fork is a most instructive instrument, and I shall not quit it until I have availed myself of its properties to exemplify the easy propagation of vibrations, of a definite pitch, through a system comparatively much less disposed to transmit those of any other pitch. Take two or more forks in unison, and furnish each of them with a single disk of the size of a large wafer, looking outwards. (See fig. 17., Art. 186. of my Essay on Sound, for the mode of attaching such a disk.) Having struck one of them, let its disk be brought near to that of the other, centre opposite to centre, and it will immediately set the other in vibration, as will be evident by the sound produced by it when the first fork is stopped, as well as by its tremors, sensible to the hand which holds it. The communication of the vibration is much more powerful and complete when a small loop of fine silver wire is fixed to one of the forks, and brought lightly into contact with the other, with its looped or convex side. Imagine now a series of such forks and loops arranged as in fig. 2, and let the first, A, be maintained in vibration by any exciting cause, as, for instance, by causing to sound a musical note opposite to its disk A, in unison with its pitch. The vibrations so excited will, as is evident, run along the whole line, though with diminishing intensity, to the last fork. Here, then, we have a case analogous to the easy transmission of a ray of definite colour, accompanied with its gradual extinction, in traversing a considerable thickness of the absorbing medium. If we would avoid the actual contact of the vibrating systems, we may conceive an arrangement like that in fig. 3, where, in place of forks, straight bars, disked at both

Fig. 2.

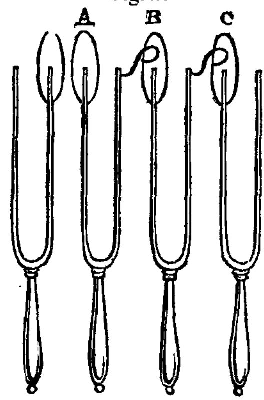
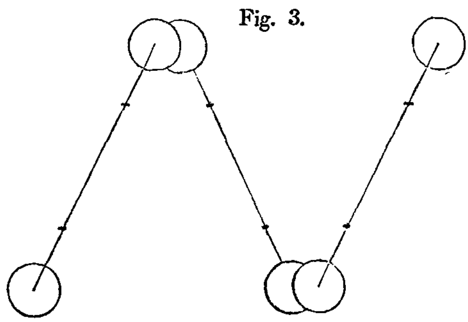


Fig. 3.



ends and supported at their nodal points, are used to form the vibrating series.

When two disked tuning forks slightly out of unison are opposed to each other, the vibrations of one are still communicated to the other, even when they differ sufficiently to produce audible and pretty rapid beats. But the communication in this case is less complete, and the sound produced feebler, than in that of perfect unison, and the degradation of intensity in the communicated sound is very rapid as the forks recede from unison. We have here a fact analogous to the appearance of a bright line in the spectrum situated between dark spaces, and as it is not difficult to imagine combinations of the nature above mentioned, in which several different notes shall be transmitted, while the intermediate one, finding no unisons, or near approaches to unison in the systems established, shall be extinguished; so by analogy we may perceive how any number of bright and dark lines may be produced in a spectrum unequally absorbed.

The case last put is entirely analogous in its principle to that of a phænomenon which is described in my Essay on Sound*, and of which, at the time of the publication of that Essay, I believed myself to have been the first and only observer, though I have recently learned to rectify that impression, and have great pleasure in referring the experiment, which is a remarkably easy and striking one, to Mr. Wheatstone, the author of so many other ingenious and instructive experiments in this department of physics. If a tuning fork be held over the open end of a pipe pitched in unison with it, the pipe will *speak* by resonance; (if the fork be disked, and the aperture of the pipe be nearly covered by the disk, the tone brought out is one of a clearness and purity quite remarkable). Now both Mr. Wheatstone and myself have observed that if *two forks*, purposely pitched out of unison with each other, so as to yield the beats of imperfect concords, be *at once* held over the orifice, the pipe will, at one and the same moment, yield both the notes, and will utter loud beats, being actually out of unison with itself. In proportion, however, as the pitch of one or other fork deviates from that to which the length of the pipe corresponds, and which the pipe alone would utter, the resonance of its tone is feeble, and beyond a certain interval becomes inaudible.

The dynamical principle on which these and similar phænomena depend is that of "forced vibrations," as it is stated in the Essay on Sound above referred to, or, more generally, in a more recent publication, (Cab. Cyclop., volume on Astronomy,) in terms as follow: "If one part of any system, connected either by material ties or by the mutual attractions of its members, be continually maintained by any cause, whether inherent in the constitution of the system or external to it, in a state of regular periodic motion, that motion will be propagated throughout the whole system, and will give rise in every member of it, and in every part of each member, to periodic movements, executed in equal periods with that to which they owe their origin, though not necessarily *synchronous* with them in their maxima and minima." The general demonstration of this as a dynamical theorem is given in the Essay on Sound already referred to, and its applicability to the transmission of light through material bodies is indicated in a note thereto appended.

The mode, then, in which we may conceive the transmission

* *Encyclopædia Metropolitana*, 2nd Div. vol. ii. p. 790.

of light through gross media to be performed, so as to bring the absorptive phænomena within the wording of this principle, is, to regard such media as consisting of innumerable distinct vibrating parcels of molecules, each of which parcels, with the portion of the luminiferous æther included within it, (with which it is connected, perhaps, by some ties of a more intimate nature than mere juxtaposition,) constitute a distinct compound vibrating system, in which parts differently elastic are intimately united and made to influence each other's motions. Of such systems in acoustics we have no want of examples—in membranes stretched on rigid frames, in cavities stuffed with fibrous or pulverulent substances, in mixed gases, or in systems of elastic laminæ, such as boards, sheets of glass, reeds, tuning forks, &c., each having a distinct pitch of its own, and all connected by some common bond of union. In all such systems the whole will be maintained in forced vibration so long as the exciting cause continues in action, but the several constituents, regarded separately, will assume, under that influence, widely different amplitudes of oscillation, those assuming the greatest whose pitch taken singly is nearest to coincidence with that of the exciting vibrations. Everybody is familiar with the tremor which some particular board in a floor will assume at the sound of some particular note of an organ; but when that note is not sounded, it is sufficiently apparent that the board is no less occupied in performing its dynamical office of transmitting to the soil below, or dispersing through its own substance and the contiguous bodies, the motion which the oscillation of the air above is continually imparting to it.

As we know nothing of the actual forms and intimate nature of the gross molecules of material bodies, it is open to us to assume the existence, in one and the same medium, of any variety of them which may suit the explanation of phænomena. There is no necessity to suppose the luminiferous molecules of gross bodies to be identical with their ultimate chemical atoms. I should rather incline to consider them as minute groups, each composed of innumerable such atoms; and it may be that in what are called uncrystallized media, the axes or lines of symmetry of these groups may have no particular direction, or rather all possible directions, or the groups themselves may be unsymmetrical. Such a disposition of things would correspond with a uniform law of absorption, independent of the direction of the transmitted ray, while in crystallized media a uniformity of constitution and position of these elementary groups, or rather of the cells or other combinations which they may be regarded as forming with the interfused æther, may be readily supposed to draw with it differences in their mode of vibration, and even different disposals of their nodal lines and surfaces, according to the different directions in which undulations may traverse them, and which may not impossibly be found to render an account of the change of tint of such media according to the direction of the rays in their interior, as well as of the different tints and intensities of their oppositely polarized pencils; of which latter class of phænomena, however, I shall immediately have occasion to speak further.

But as my present object is merely to throw out, as a subject for examination, a hint of a possible explanation of the phænomena of absorption, on the undulatory theory, I shall not now pursue its application into any detail, nor attempt the further development of particular laws of structure competent to apply to this or that phænomenon. I will, however, mention one or two facts in acoustics which appear to me strongly illustrative of corresponding phænomena in the propagation of light. The first of these is the impeded propagation of sound in a mixture of gases differing much in elasticity as compared with their density. The late Sir J. Leslie's experiments on the transmission of sound through mixtures of hydrogen with atmospheric air sufficiently establish this remarkable effect. It would be desirable to prosecute those experiments in larger detail, but hitherto I am not aware of anybody having ever repeated them. It would be interesting, for instance, to inquire whether the impediment offered by such a mixture of gases be the same for all *pitches* of a musical note, or not; and how far this phænomenon might be imitated by mixing actual *dust* of a uniform size of particle, such as the dust of Lycoperdon, &c., or aqueous fog, and how far such mixture would affect unequally sounds of different pitches.

The other fact in the science of acoustics which I would notice as illustrative of a corresponding phænomenon in photology, is one observed by Mr. Wheatstone, which I have his permission to mention. In attempting to propagate vibrations along wires, rods, &c., to great distances, he was led to remark a very great difference in respect of facility of propagation between vibrations longitudinal and transverse to the general direction of propagation. The former were readily conveyed with almost undiminished intensity to any distance; the latter were carried off so rapidly by the air, as to be incapable of being transmitted with any considerable intensity to even moderate distances. This strikes me as obviously analogous to the ready transmissibility of a ray polarized in one certain direction, through a tourmaline or other absorbing doubly defracting crystal, while the oppositely polarized ray (whose vibrations are rectangular to those of the first) is rapidly absorbed and stifled, *i. e.* dispersed, by the agency of the colouring matter which acts the part of the air in Mr. Wheatstone's experiment, and self-neutralized by the opposition of its subdivided portions as above explained.

Slough, October 19, 1833.

LXIV. *Remarks on* Mr. Barton's *Reply, respecting the Inflection of Light. By the Rev.* B. Powell, *M.A. F.R.S. Savilian Professor of Geometry, Oxford.*

To the Editors of the Philosophical Magazine and Journal.

Gentlemen,

I DID not see your Number for September last, containing Mr. Barton's reply to my former paper, till very lately, and now hasten to send a few brief observations, which that reply seems to call for, and which I trust you will favour me by inserting in your Journal.

In the first place allow me to say that the courteous tenour of Mr. Barton's paper assures me that he will regard my present communication with the same candour as he has done the former; and in that spirit of candour I will proceed at once to the essential questions at issue.

The important and conclusive experiment is that in which the aperture has *straight parallel edges.* Here Fresnel's formula applies directly, and accords most exactly with the phænomena. This is evident both from what I have stated (Lond. and Edinb. Phil. Mag., vol. ii. p. 431–2), and from the exact experiments of Professor Airy, described in my postscript (*Ib.* p. 433). On this part of the question I do not perceive that Mr. Barton alleges any result of his own of an opposite kind. The only difficulty is about an experiment of Newton's. (Optics, book iii. obs. 5.) Now this experiment, as I before observed, is involved in considerable ambiguity. I am not aware whether Mr. Barton has succeeded in reproducing it *with all the concomitant circumstances* as described by Newton, viz. the "long trains of light" which he speaks of, &c. These are as essential to be explained as the appearance of a dark space in the centre. I have repeatedly tried to verify this experiment, but entirely without success; and I am much inclined to believe that there were some circumstances in the conditions of the case of which we are not fully informed. It is surely, then, most imperatively incumbent on us to ascertain carefully all the conditions, before we allege it in opposition to the united testimony of all other experiments.

But with respect not only to this, but also to the other ex