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ABSTRACT

The life and work of Isaac Newton and his investigations of light and color are described in detail. Notes include preliminary observations of chromatic dispersion; dispersion by an equilateral prism; the "Experimentum Crucos" or the composite nature of white light; the nature of colored light and illumination; transmissions and reflections; and the reconstitution of white light. (Author/SA)

Newton's Investigation of Light and Color
(Experiment # 7)

NEWTON'S INVESTIGATION OF LIGHT AND COLOR

Historical and Experimental Notes

N.S.F. Grant 74-17738-01

Samuel Devons
May 1975

NEWTON'S INVESTIGATION OF LIGHT & COLOR

Historical Notes

Perhaps the greatest obstacle to an appreciation of the magnitude of Newton's achievement and the full significance of Newton's revolutionary ideas concerning white light and color is, that once propounded and accepted, they seem almost self-obvious; so obvious that it is hard to conceive how there could be any other view of the matter. Yet we know from the way Newton's ideas were first received, that it is not something intrinsic in the nature of the phenomena, but in the way we have learned - following Newton - to regard them. There were, before Newton, other ways of regarding light; some with a long history, some firmly embedded in a comprehensive philosophic system; most apparently finding some support in experience, and to many who held such views, Newton's were hard to comprehend and even harder to accept. Newton's original exposition, his first published work, in 1671, which must have seemed to him, as it does now to us, convincing in its experimental evidence and compelling in its logic - was met with misunderstanding, skepticism, and direct hostility There ensued a five-year-long public debate (in the pages of the Philosophical Transactions of the Royal Society) which ended not only by clarification and some reconciliation, but also by the expiring of some critics and the exhaustion of Newton's patience.

Many factors contributed to this debate: philosophical prejudices, personal rivalries, semantic confusion, and not least, ambiguities and inadequacies in Newton's own initial account of his experiments and conclusions. Newton had been experimenting in optics for many years, designing and constructing and testing optical instruments, examining optical materials, and pondering deeply on the many problems he encountered. For several years he had lectured on optics in Cambridge; his experience had grown and his ideas developed. Now in a few pages he lays out - in a beguilingly simple narrative, how step-by-step his experiment leads him to his inexhorable conclusions. The experiment evidence, properly laid out, seems to Newton to speak so clearly, that he cannot imagine that those who do not share his experience and insight may have as much difficulty in picturing precisely what has been observed, as in accepting the conclusions that follow from the observations.

It was not simply a matter of rival theories of light and the production of colors; although that was indeed the issue for some critics. For the task of examining the physical nature of light, the science of optics was still a relatively inarticulated subject. Many of the elements of both scientific vocabulary and experimental technique were known, but hardly in any systematic and generally used and accepted form. Rays of light, images, slits, apertures, prisms, lenses, refractive power, the geometrical features of refraction and reflection, all these notions were more or less current, but usually in a particular context, rather than part of a conceptual scientific vocabulary. A term which might have evoked some distinct concept to Newton himself, could have created a quite different, or confused impression on someone not sharing his experience, let alone his viewpoint. Experiments on light and optics were not yet at a stage where there existed generally understood and accepted patterns of standard procedures and basic components - with all their implied assumptions and approximations - to be exploited in a particular way and to demonstrate some new phenomenon. Each experiment represented a new arrangement, in toto as it were. The essential functioning of the component parts and their relation to the whole was rarely something that was, or could be, clearly expounded - or if expounded fully comprehended. Detail and principle, the essential and the incidental, were neither clearly demonstrated nor easily discerned. Optics in Newton's time was an old and venerable science; but the physics of light was new and unformed.

If we stress the difficulties that Newton's contemporaries might have experienced in fully grasping the nature of Newton's work from his published account, it is not so much to suggest that had he presented a much more detailed explication his views might have found a readier acceptance, as to emphasise the great difference between experiments as demonstrations of what is know, (or believed), and experiments as a means of discovery. When the conclusion is foregone, how readily does one select what one believes to be essential to one's argument, and how readily one can dismiss or even overlook what one considers irrelevant circumstance, unimportant "detail"! With the road well laid and the destination clearly in view who bothers to examine each clue along the track, to take bearings constantly, and constantly to examine - and occasionally mistrust - one's instruments? This is only demanded of the explorer. Newton may have omitted to explain to his readers all that he had observed and scrutinised before he reached his goal, but we can hardly conceive that he himself had overlooked much, or taken too much for granted. Indeed as the debate with his opponents proceeds we see him supplying progressively more detail, expounding and elucidating each point more fully, meeting specific criticism with further evidence and fuller argument. There are not so much new arguments or new observations to meet unforseen weaknesses in his views, as matters which he had been aware of all along, that he had hoped he could leave to the imagination of his readers, but is now prepared patiently, though grudgingly, to supply. For Newton is not so much debating with his opponents as reiterating publicly the dialogue he has already held privately with nature. To recapture the spirit of Newton's discovery it is to this private conversation we must listen. Discourse with nature, by experiment, is Newton's prime teacher: and it is our's too if we wish to understand how he learned, and what he has taught us. Or in Newton's own words:

Historical Notes continued

"For if the experiments which I urge be defective, it cannot be difficult to show the defects but if valid then by proving the theory they must render all objections invalid."

2. There are several sources from which one can attempt to reconstruct the train of experiments, observations and reasoning which led Newton to his basic theory of color. Chronologically:

1) The optical lectures at Cambridge and other notebooks and correspondence of this period (1661-1671).
2) The debate, published in the Philosophical Transactions (1671-1676), stimulated by Newton's 1671 paper of 1671/72.
3) Newton's Optick's (1704/1718/1730).

Optics, ranging from the practical construction of instruments to the mathematical formulation of principles, was a central interest of Newton's from the period 1660-1675, and many of the tasks he undertook, the problems he encountered, and the phenomena he observed clearly gave him frequent cause to ponder on the nature of colors and the causes of their appearence. Historians seem to disagree - or at least express uncertainty about the precise chronological sequence of his investigations. Did he experiment with the prism before or after his concern with the chromatic aberrations of telescope lenses? When did he first recognize the correlation of "refrangibility" with color, and at what stage did the idea occur that this difference in refraction separated the colors rather than generated them? There seems little prospect of settling these historical niceties definitively. Different aspects of Newton's concern with light were surely inextricably interwoven, and though he may have been primarily concerned with one or other aspect at any particular moment, it is almost inevitable that manifold interests were at work simultaneously even if they were not being deliberately pursued.

For our purpose it should, and will suffice to recognize some four sorts of observation and experiment:

i) Early observations relating to chromatic aberration of lenses, instruments, etc.
ii) Early observations of dispersion by prisms
iii) Deliberately designed prism experiments to text a more-or-less fully conceived <u>theory</u> of color; especially the <u>experimentum crucis</u>.
iv) General experimental tests of color appearances, color mixing, etc.

and to discuss the experimental particulars in this order. Roughly, this is the order in which these matters appear in Newton's first paper and the subsequent debate (Item (ii) above), or at least one may infer some such sequence from Newton's narrative and its numerous allusions and detours.

But there are more practical considerations. An attempt to reproduce the path of observation, experiment and reasoning which raised such animadversions and misunderstanding amongst his contemporaries must recognize that the optical experiments were for most part made with sunlight. Impressive and convenient as it is, the sun is hardly the "ideal" source of light, that abstraction to which one resorts so readily in expounding or illustrating optical principles today. (If one experimented with sunlight today it would be to study the sun rather than the nature of light!)

The sun, as a source of light, is, inter alia, of finite angular size (approximately 30 arc-minutes ($\frac{1}{2}^{\circ}$) in diameter), at a distance virtually infinite in comparison with the scale of any experimental apparatus. Thus from any one point of the sun the (divergent) rays that enter any part of the apparatus are treated as parallel; but not so rays from different points of the sun. One cannot, of course, in any simple, obvious direct way, block out all the light from the sun except for one small region, as to achieve an effectively point source and thus completely parallel light. But by the use of slits, screens and more sophisticatedly with lenses, an approach to the ideal of parallel light was, in effect made in pioneering optical experiments. But the need for the signifance of parallelism, the precise manner in which it was created, and the degree to which it was attained, - all these factors were rarely fully recognized and appreciated. Even when they were - perhaps intuitively - recognized in practice, the clear and systematic explication of their significance in the reports and writings of Newton's time was rare.

Newton himself was certainly fully aware of these factors in his experiments, but the rather haphazard manner in which he deals with them - piecemeal and usually in response to some particular criticism - illustrates the general lack of a systematic vocabulary of optical techniques and principles in his time. "Ideal" optical arrangements were not only far from achieved, they were usually not explicityly, or in a generally acceptable way formulated. If we are to try to reproduce the success attained by Newton, and the obstacles that he had to surmount - both in convincing himself and his opponents, then it is with actual imperfect sources of light, rather than with idealized arrangements, made possible by the subsequent development of optics, that we must work. Obviously the sun itself would be the proper choice; and if this is impracticable, then some, equivalent, source which replicates as far as possible (and in a manner which is not concealed!) the real virtues and limitations of sunlight. This is far from trivial: in fact, it is the most important aspect of any attempt to recreate - by sunless but faithful laboratory experiments - the proper significance of Newton's work. We return to this question below. Meanwhile we notice that the observations of chromatic aberration need not invoke the properties of shafts of sunlight in any special way. The sun here provides simply a source of general illumination; it, or some other source can be used equivalently, just as Newton describes in his own observations. So one can, start with some experiments that do produce phenomena as Newton - and perhaps his contemporaries - saw them. This may not be the exact historical sequence; but it is not violently anachronistic, and at least the observations can be faithful and meaningful.

3. It is a matter of taste and judgement how much (or little!) historical or other reading should precede experimentation. Ideally, one might wish to begin experimenting with the sort of background, experience (and prejudices) possessed by the pioneer in the field; which means familiarity with an earlier phase of science and its history. But it hardly is realistic to expect this background to be supplied by extensive reading in the primary literature. Some synoptic, secondary sources (plus verbal instruction) are the best that one can usually expect. If one experimental-historical inquiry is preceded by another, which provides a natural introduction, so much the better. For Newton's Optics the precursors are Greek-Arabic-Medieval Optics culminating in Witelo and Dietrich at the end of the 13th century; the resurgence of optics in the 16th/17th centuries exemplified by Kepler's Dioptrice (1611) and Descarte's Dioptric (1637); and the more immediate background provided by the publications of Hooke (Micrographia 1665); Robert Boyle (Experiments and Considerations Touching on Colors, etc., 1664); Grimaldi (Physico Mathesis 1665), and Erasmus Bartholinus (Exp. Crytalli Islandi -- 1669). (For a list of useful introductory material see References in Bibliography)

Newton's first paper of 1671/1672 (referred to as N. I), and parts of Book I of the Opticks are suggested as a minimal basis of primary readings, and as a framework for an experimental inquiry.

II: EXPERIMENTS

(~~see~~ also Blue Book. pp.43-45c)

1. Preliminary Observations of Chromatic Dispersion

Experiments described in Newton's Opticks (Dover Edition) pp.20-26, Prop. I. Theorem I. Experiments 1.,2.

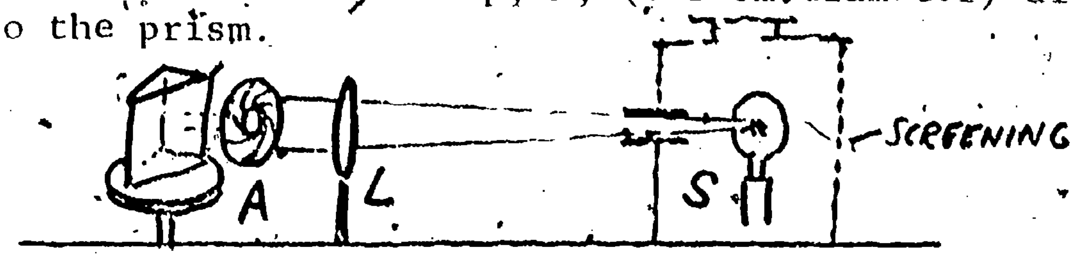
These are easily reproduced experiments; as Newton writes " a novice might more easily try them". No special light sources needed. Note that Newton used an artificial source (candle) in one of them! A fairly large (2" diameter should suffice) bi-convex lens of focal length 15-20 cm. can be used conveniently in Experiment 2. If light background is a problem, one can substitute for Newton's two-colored card, color-transparencies (filters) with suitable fine markings, or color film transparency with fine detail, and these can be illuminated from the rear.

2. Dispersion by an (Equilateral Prism)

To simulate the shafts of sunlight without over-idealizing or under-realizing the capabilities of these experiments, is, as mentioned, the most important problem.

Obviously a luminous object at a distance sufficiently large that from each point of it the light could be considered parallel, and yet the whole subtending $\frac{1}{2}^{\circ}$, is as impractical as using the sun itself! (It would have to be several hundred meters away, and therefore several meters in diameter!). But since one needs only a light source which emits - more-or-less uniformly - over the angular range employed, i.e. approximately $\frac{1}{2}^{\circ}$, one can simulate this with a small bright source at the focal point of a lens.

A carbon-arc, or a more modern counterpart (e.g. a gas-filled concentrated-arc lamp made by Sylvania Electric Products) can provide an intense 'white light' source S of some 3 - 4 mm. diameter. Placed at the focus of a 30 - 40 cm. focal-length lens L, this light source is transformed into a 'source-at-infinity' with an angular spread of 1/100. The diameter of the lens need not be much larger than the 'beam' of light one intends to use: 4 cm. diameter is ample. It is convenient to use a variable stop, A, (0-2 cm. diameter) after the lens, and close to the prism.



The quality of the beam transmitted through this aperture can be observed on a distant screen, L meters away, where it should appear as a uniform disc of light of diameter L cm; and this diameter should be more-or-less independent of the size of the opening A.

With such a light source, and without the use of additional lenses, the sharpness or diffuseness of spectral-images, etc., is determined primarily by the linear scale of the experimental layout and the $\frac{1}{2}^{\circ}$ angular divdrgence of the light, unless additional apertures are used to select a restricted angular range of the light.

Thus Newton using a 22 foot long room observed a "breadth" of some 2 5/8" (= 22 ft. X 1/100), which is much larger than the hole of 1/3" diameter in the window shut. Twenty-two feet may well be inconveniently large; so a roughly half-scale version of the experiment may be used:

Aperture in front of prism $\sim$ 5 mm. diameter
Distance from prisim to screen $\sim$ 3 meters
Size of image $\sim$ 300 X 1/100 cm. = 3 cm. ($\approx 1\frac{1}{4}$")

The "white-light" source mentioned above is stated by the manufacturers to have an equivalent temperature of some 3000° Abs. The sun's surface temperature is $\sim$ 6000° Abs., so that one might expect the artificial light to be much redder than sunlight. In fact it is not a bad match to ordinary sunlight (at the earth's surface) which is presumably much redder than the primary light on account of atmospheric filtering.

Since the interpretation of the <u>shape</u> of the spectrum was central to Newton's ideas - and the ensuing controvery - it was, as Newton recognized, important to show that this could be controlled or changed. (Newton promptly addresses himself to this question (April 1672) in reply to comments he receives from the Royal Society on his first publication). In several ways this maybe done, with results demonstrably consistent with Newton's interpretation.

(a) A long-focal length lens (focal length ~2-3 M.) can be used to focus the diaphragm A onto the screen. Then, as Newton reports , "...the streight edges of the oblong image were distincter than they would have been without the <u>Lens</u>."

(b) Experiments with a source producing less angular divergence than the sun, to wit, a planet. Quoting Newton again:

"Considering that the rays coming from the Planet <u>Venus</u> are much less inclined one to another, than those, <u>which</u> come from the opposite parts of the Sun's disc I once tried an experiment or two with <u>her</u> light. And to make it sufficiently strong I found it necessary to collect it first by a broad <u>lens</u>, and then interposing a Prism between the <u>Lens</u> and its <u>focus</u> at such distance, that all the light might pass through the Prism; I found the <u>focus</u>, which before appeared like a lucid point, to be drawn into a long spl[illegible]d line by the Prism's reflexion." (Sic!-surely a misprint for 'refraction'?)

The spectrum of Venus observed might make a good "special project". But more prosaically and practically, the influence of the <u>angular</u> size of the light source can readily be studied with the artificial source, viz: Change the lens L to one of longer focal length, say 60-80 cm. The effective angular size is reduced from 1/100 to 1/200. (Not as good as Venus; but, the change in the shape of the spectrum will be quite pronounced!)

3. Supplementary Observations (c.f., N.I. pp. 3076, 3077)

a) Check influence of size of aperture A on shape of spectrum.

b) Check influence of thickness of prism-glass traversed (By small lateral displacements of prism).

c) Note how position and shape of spectrum depends on prism orientation (observe "minimum deviation"). Particularly relevant to Pardies criticism (Ref. i).

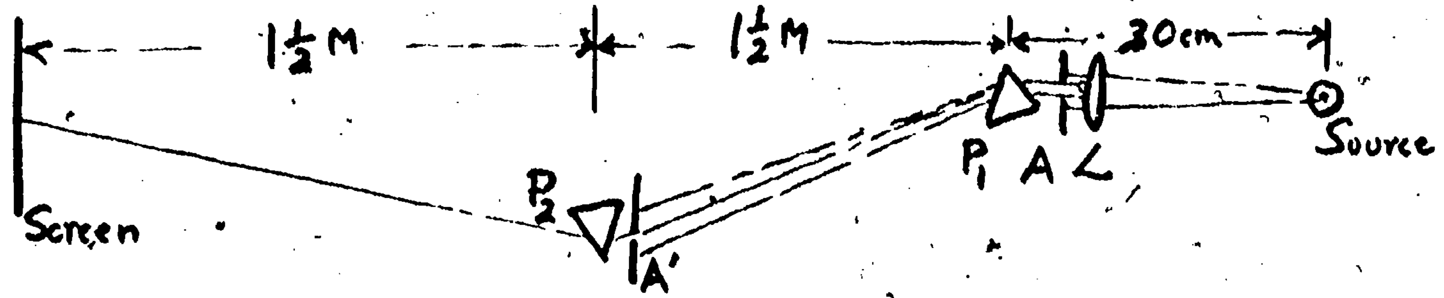
d) Verify linearity of rays emergent from prism - by moving the screen.

e) Repeat experiment with two similar prisms (p. 3076), showing colour-production is not due to surface irregularities.

4. Experimentum Crucis

This is the one experiment that Newton returns to time and again, as the most direct and conclusive verification of his basic principle: The composite ("difform", "mixed", "comingled", etc.) nature of white light. It should be performed with the thoroughness it deserves.

There are, in Newton's own writings, several versions and subsequent scientific and historical documents spawned innumerable variations - many ficticious, spurious, and even incorrect. The description in N.I., p. 3078, (which is essentially the same as the fuller account in Newton's second reply to Pardies (Ref. ii, p. 5016) although the apertures are not in precisely the same location in the two versions), is followed here.



With the layout approximately as shown, the length of the spectrum at the second aperture, A' will be about 6 cm. and width about 2 cm. (Aperture A about 6 mm. less). A' should be an adjustable slit, with openings in the range 1 to 5 mm. Both P_1, P_2 are set originally in the symmetrical positions (minimum deviation).

Turning P_1 about its axis by a few degrees changes both the color and the position of the light on the screen; turning P_2 changes neither (at least to first approximations). The effect of displacing P_2 from the position of minimum deviation, and of altering the apertures A,A' can then be studied - and explained. One can also examine the effect of transposing A' to the opposite side of the prism.

That the colored rays are not associated with some sort of curved trajectory - (as might be inferred from some earlier, cartesian, conjectures) - can also be readily checked: Simply by changing the position of the screen and noting the position and size of the colored image (N.I. p. 3078). Another demonstration of this is the use of two prisms, one transverse to the other. The spectrum is now displayed at 45° to the axis of both prisms (Ref.iii, p. 5092).

The light emergent from P_2 can be further 'analysed' by another prism P_3, to verify that successive refractions do not change the color of 'homogeneal' light. Likewise, the light may be reflected from an ordinary mirror, or scattered from a white surface without change of color.

It is this "experimentum crucis" and its variations that form the basis of Newton's principle that the element in optics is a ray of colored light; 'colored' in the particular sense that it possesses a definite refrangibility, elementary in the sense that subsequent physical processes - reflection, refraction, transmissions - do not change its color or refrangibility. Newton's revolutionary idea is not simply the assertion that white light is composite; it is also the introduction of the possibility of a persistent, colored ray or beam of light. All earlier investigations had interpreted color as some sort of modification of white light introduced by its passage through apertures and/or refracted media with boundaries, and not necessarily, or even usually, a uniform modification of the whole beam. Moreover, successive transmissions introduced successive changes in the color-structure of the light. Color then, was a transient property of light in particular circumstances. In contrast, for Newton, color was a basic intrinsic property of light; and the ideal light was a ray of uniform, constant, single color.

5 Nature of Colored Light and Illumination

In Newton's scheme there are three classes of light:

a) Pure colors, of a particular, constant refrangibility. No further separation possible.

Experiments continued

b) Light which may appear similar to a pure color, but is nonetheless mixed. By refraction, transmission, etc., its components can be separated.

c) White light, a special combination of all colors, "...the confused agreggate of Rays indeed with all sorts of colors, as they are promiscuously darted from the various parts of luminous bodies." (N.I. p. 3082-3083)

Numerous experimental tests can be made of this conceptual framework; it can also provide a ready explanation of some well attested phenomena - e.g. the colors of the rainbow, or the different colors of semi-transparent objects viewed in reflected or transmitted light (N.I. p. 3084)

6. Transmissions and Reflections

Use a conical flash with various colored solution Observe the transmission (and reflection) of "monochromic light" of different colors, selected by prism-refraction. Also view different colored minerals - cinnebar, red-lead, indigo, etc.- illuminated by different light.

7. Reconstitution of White Light

White light can not only be analysed into its components, it can also be synthesised from them. The experiment described by Newton (N.I., p. 3085-3086) can be reproduced - on a somewhate reduced scale.

A 30-50 cm. focal length lense, of 3-4 cm. diameter and placed 30-60 cm. from the prism, is satisfactory. Reconstituted white light can be observed on a screen some 100-40 cm. from the lense.

From Newton's description of this experiment - and from a scaled-down reproduction of it - it appears that he is focussing an image of the aperture just in front of the prism on to the screen. Images corresponding to different colors will be separated by dispersion, by an amount of approximately $\Delta X = \ell \times \Delta\theta \times M$. (ℓ is the distance between the aperture and the prism, $\Delta\theta$ the typical angular dispersion, and M the optical magnification. Since is only a few inches, say 4"; $\Delta\theta \sim \pm 2/3$, and M about 2, the color separation on the screen is typically $\pm$ 1/10". This is much smaller than the magnified image of the aperture Newton uses, which is $\sim$ 2 x 1/3" = 2/3" diameter, so that will be good overlapping of the different colors. (Notice the difference between this use of a lens, and when used to sharpen the spectrum. c.f. p. 7(a), above). (N.I., p. 3087)

Experiments continued

There are other versions of this experiment to reconstitute white light. In Opticks, Exp. 11, pp. 142-143, a second prism is used in place of the lens. Later, Opticks Prop. XI, Prob. VI, pp. 186-189, a more sophisticated arrangement with a lens symmetrically placed between two prisms is used (Fig. 1). By the principle of the reversibility of the rays of light, the whole spectrum can be recombined into a white circular patch of the same size, and in the same position relative to the second prism as is the aperture to the first. (Typical scaled-down values: f=25 cm.; separation of prisms 90 cm.; aperture close to prism. For the symmetrical arrangement the distance between object and image is 4f.)

Figure 1 (on page 11a following)

The effect of changing the apertures, and the position of screen should be observed and explained!

Interception of any part of the spectrum, at the lens, results in a colored image (not a pure color!). More striking support of Newton's hypothesis of the complexity of white light is provided by experiments in which all but a narrow segment of the spectrum is intercepted at the lens (Fig.2, p11a) by a diaphragm B. A more-or-less uniform color is seen on the screen. (Observe the effect of changing the primary aperture A). As aperture B is moved across the spectrum, the color at the screen S changes successively from red to violet or vice-versa. If this change is speeded up, by using a slotted wheel

Figure 2 (on page 11a following)

(Typical Dimensions AP=4cm.; AF~FS~45cm; f of lens=24 cm.)

which can be rapidly rotated, the appearance to eye is of a uniform whitish image. White light has now been reconstituted, not only by simultaneous, but also by successive superposition of all its constituent colors (Ref. iii, p. 5097); and by the latter means the transition from separate colors to whiteness can be made gradually! (See also Opticks, Prop. VI, Prob. II, pp. 154-158, and Exp. 12, pp. 144-145).

In yet another demonstration of the same principle, a board, covered with numerous strips of colored paper is illuminated by strong light, and the light reflected from this surface is used to illuminate a (neutral) white paper screen. If the distance between board and screen is sufficient the screen appears white; when closer to the board, remnants of the colors can be discerned.

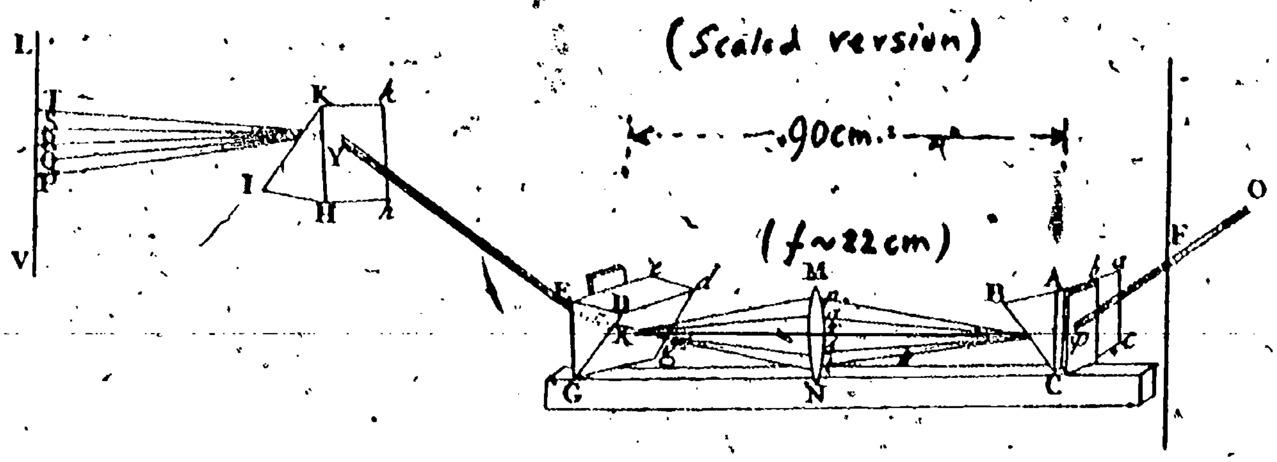


Figure 1 (Newton's Opticks, p. 187)

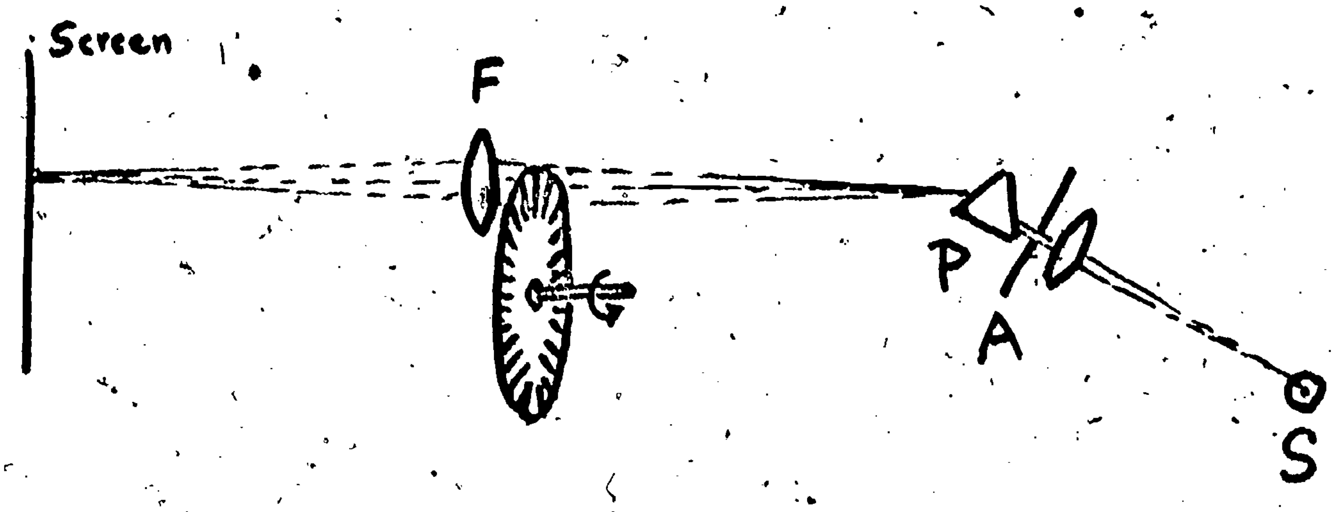


Figure 2 Color-Mixing

Experiments continued

One final example: A fine froth of soap-bubbles illuminated by white light when examined close-up shows distinct, localized colors (The colors of their films, as described originally in Hooke's Micrographia); At some distance these appear to merge into a uniform whiteness. (Ref. iii, p.5101, 1693)

There are more elaborate experiments to display the differences between composite light which looks white, and natural white light. For example, using two prisms and light sources, blue and red light when mixed on a screen appears whitesh; but examination through a prism readily reveals its true composition! (Ref. iv, p.6088.) These experiments are partly to refute Hooke's original hypothesis that white light - and indeed all colors - can be compounded of two basic colors: yellow and blue. (c.f. Ref. v, p. 6108)

It is well worth remarking that Newton was always fully aware of the difference between what we might call the psychological sensation of color and the physical concept of a pure color (of a ray of light, etc.). Apparent identity of appearance (sensation) is nowhere taken as conclusive evidence of physical identity; but change in appearance is taken as evidence for some change in the physical composition. Of course there are also many instances, - particularly in the successive transmission through prisms of rays of pure color - where the constancy of appearance is consistent with Newton's hypothesis, and therefore in support of it. But it is the impossibility of effecting any visible change by any physical means available, that is the real test of the purity or elementarity of the individual colored rays.

Postscript

An attempt to replicate these beguilingly "simple" experiments of Newton soon reveals that there are recurrent subtleties in the (geometrical) optics involved, which Newton himself is not always at pains to explicate fully, and which were surely neither familiar to the optical art of his day, nor obvious to his contemporaries. For some these difficulties were really a source of confusion, for others they provided an opening to criticise the validity of his experiments, or more often, his conclusions from them. Pardies was at first misled, later convinced (Ref. i, ii); Hooke, defending his own theories, is highly critical of the dramatically new Newtonian hypothesis, (Ref. vii); the great Huygens genuinely skeptical (Ref. iv); and the lesser lights at Liege quite unequal to the task of reproducing Newton's results, let alone fully understanding them(Ref. vi). But beyond these reactions to Newton's theory of white light and prismatic colors, there was another real complication whose full significance, or even the relation to his experiments, was only partly grasped by Newton himself. This was the observation by Grimaldi, a few years earlier, that

Postscript continued

colors appeared near the edges of shadows cast by fine obstacles and slits in the path of light. To be sure the dimensions of apertures in this case were of a different order from the rather coarse openings (even the smallest of them) used by Newton; and Newton was correct in disregarding Grimaldi's findings as irrelevant to the main issue at stake in his own work.

Yet the observations of Grimaldi, like the colors in their plates, bubbles, films described by Hooke, were real enough, and Newton could not long ignore them if he were to defend, and extend, his own theory of light and color. These matters seem to have occupied Newton's attention shortly after he had concluded his findings on the nature of white light; and he set out his extensive ideas and speculations in a letter to the Royal Society in 1675. This so called "Second Letter" may be read as a preliminary draft of a large part of the Opticks, which was published some 30 years later (- when his major critics, Huygens and Hooke, were both dead. It is here, in the letter of 1675, and later in Opticks, that one finds the full expression of Newton's hypotheses and speculations about the nature of light, the famous "corpuscular" theory, the theory of alternate "fits" of easy reflecttion and transmission; together with remarkably precise experiments on "Newton's Rings" in which, effectively, the wavelengths of different colored light is determined for the first time.

There are only occasional hints of this later conceptual edifice in the pre-1675 writings of Newton. The contrast between the 'first' paper (1671/1672) and the 'second' is striking. In the first, and in its defense, he denies all pretensions to hypothesizing: his experiments demonstrate the true nature of light; the second is a long elaboration of an involved hypothesis of particles and ether, supported from time-to-time by appeal to experiment. In the Opticks one sees an attempt to combine the experimental-logical style of his earlier work with the wider embrace of his later speculations and explanations. Ironically, Newton's earlier conclusions so well-grounded in inference from experiment aroused immediate sharp criticism, while his Opticks, with its far more ambitious and speculative hypothesis was acclaimed. But of course by 1705 Newton's reputation rested on a far more imposing base than his optical work. It required, as we know, a century or so before his ingenious and compelling ideas were really challenged, and then overthrown. But his early work, his masterly analysis of the nature of white light, endures, not only as, perhaps, the greatest single contribution to the understanding of the nature of light, but also a great pioneer example of the power and purpose of scientific experiment and inference.

Details of Apparatus:

This experiment uses essentially standard, inexpensive items commercially available.

1. Source of Light: The crucial item is, as already emphasized, the light source. The most convenient is a modern version of the high-intensity arc, but this is not inexpensive! (We have used the Cenco 100 watt lamp, #87341 (about $50/Life: 375 hours) with the power supply #87345 (about $200)).

Alternatives are:

1) The sun. Cheap, if available. A simple mirror arrangement just near the entrance aperture to the dark-room can be used to keep the sunlight-beam in convenient position.

2) A high-intensity filament lamp (eg. 36 Watt car lamp). By suitable blackening of the glass, an effective source size of some 4 or 5 mm may be arranged, but the brightness will be considerably less than optimum. (Also the color is more "yellow" than sunlight)

3) An old fashioned arc-lamp. Excellent brightness, but messy to use; - unless an automatically regulating arc is used, which is expensive. (Simple arc: Sargent-Welch #3680K; Leybold market an expensive automatic model)

In all cases to simulate the sun the source is placed at the focus of a converging lens of focal length, f, chosen so that $f \sim 100$ d, where d is the "diameter" of the light source. This simulates the sun.

2. Optical Bench and Fittings: Only the simplest optical bench, with fittings to carry slots, screens, lenses, etc is necessary, but robust equipment is probably a sound investment!

A graduated bench is convenient, but certainly not essential. The equipment listed by Sargent Welch #'s 3621, 3624, 3626, 3620(A) or Cenco #'s 72220, 72210, 72322, etc., should be adequate. One 100 cm and one 200 cm bench together suffice for most experiments described above.

3. Lenses: A few bi-convex lenses 20-50 focal length of moderate quality, and with diameter of about 4 cm.; with lens-holder (e.g. Cenco #72288 or Sargent Welch #3629).

4. Prisms: (Three) Equilateral (60°) prisms (glass or lucite) with 1" face width and 2" - 4" high are adequate.

Details of Apparatus continued

5. Slits, Diaphragms: A simple fixed slit of width ~ 2 mm., which can be turned about its axis to obtain a variable width, is sufficient (to select part of the spectrum). A more elaborate adjustable slit is convenient, but not essential.

An adjustable iris (0-½" diameter) - (from an old camera?) - of some sort should be available. A pair of simple platforms, which can be turned in their mounting, is also needed to mount the prisms.

6. Light Screening: Apart from the obvious need for a dark-room, it is necessary to screen off stray light from source, and especially so if more than one optical set-up is being used in the room. If the layout in the room is convenient this may be accomplished with appropriate black curtaining; but, a more flexible (and maybe safer) arrangement is a metal box enclosing the source, and equipped with a small inexpensive blower to aid convection (the lamp dissipates 100 W.). See accompanying diagram.

7. Miscellaneous: Many other items - colored objects, screen, etc. - are easily home-made.

For the observations on color mixing an ordinary comb may be used; or alternatively, a card-wheel (4" diameter) with radial slots about 1" long, 1/10" wide and spaced ¼" apart. This can conveniently be spun by hand at the appropriate speed. (See p. 11a, Fig. 2)

CHRONOLOGY

1589 - Giambattista della Porta (1538-1615). "Natural Magic", 2nd Edition 1589. Systematic treatment of spectacles.

1604 - Johannes Kepler (1571-1630). "Ad Vitellionem Paralipomena". (Mathematical theory of image formation and vision - point-to-point - based on rectilinear theory of light and an approximate law of refraction: r ∝ i). Also 1611 Dioptrice (Principle of spectacles, telescope).

1609 - Galilei Galileo (1564-1642). Telescopic Observation of Moons of Jupiter, etc. 1610. ("Siderial Messenger").

1621 - Snell's Law (Willebrod Snell, 1580-1626). Published in Risner's Optica.

1637 - René DesCartes (1596-1650). Dioptrice.

1640 - Fermat-Descartes Controversy (Pierre Fermat 1601-1665).

1648 - Joannes Marcus Marci (Prague). "Thaumantias; Liber de Arcu coelesti". Refraction and color of light related.

1661-66 - Isaac Newton. Early experiments in optics, color, etc.

1664 - Robert Boyle (1627-1691). "Experiments and Consideration Touching Colors..."

1665 - Robert Hooke (1635-1703). "Micrographia". Microscopy and colors of their films, etc.

1665 - Francesio-Maria Grimaldi (1618-1663). "Physico - Mathesis de Lumine Coloribus et iride". Observations of Diffraction.

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1669-71 Newton's optical lectures at Cambridge

1671-72 Newton's "First Paper" on Light and Colors. (Philosophical Magazine of the Royal Society). Hooke's commentary on Newton's paper (unpublished: Reported in Birch, "History of the Royal Society". 1756).

1672-76 Criticisms on Newton's Papers and Newton's replies and elaboration (Pardies, Hooke, Huygens, Linus, etc.).

Chronology continued

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1704 - Newton's "Opticks", 1st Edition; Second Edition 1718; 4th Edition 1730.

1729 - Newton's "Optical Lectures" Published.

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(i)	Pardies' first letter. April 1672. (No. 84) p. 4087.	pp. 79,86
(ii)	Pardies' second letter. May 1672. (No. 85) p. 5102.	pp. 97,99
(iii)	Newton's reply to Hooke's criticism. Nov. 1672. (No. 88) pp. 5083-5103.	pp. 116-135
(iv)	Letter from "Huygens". June 1673 (No. 96) pp.6086/87. Newton's reply pp. 6087/92.	pp. 136-142
(v)	Newton's note on color mixing. April 1673. (No. 97) pp. 6108/11.	pp. 143-146
(vi)	Letters from Lucas, Linus, etc. and Newton's replies. 1674/75. (No. 110) p. 21, (No. 121) p. 499. 1675/76 (No. 123) pp. 503,556. (No. 128) pp. 692, 698.	pp. 148-169
(vii)	Hooke's criticism of Newton's First Paper. In Birch's History of the Royal Society.	pp. 110-115

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(All in English translations)

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Fermat		pp. 278-280
Bartholinus		pp. 280-283
Huygen's	(Traite de la Lumiere)	pp. 283-294
Grimaldi	(Physico-Mathesis...)	pp. 294-298
Newton	(First Paper)	pp. 298-305
	(Opticks - 4th Edition)	pp. 305-308

Definitions.

1 I call that Light homogeneal, similar or uniform, whose rays are equally refrangible.

2. And that heterogeneal, whose rays are unequally refrangible.

Note. There are but three affections of Light in which I have observed its rays to differ, *viz* Refrangibility, Reflexibility, and Color; and those rays, which agree in refrangibility agree also in the other two, and therefore may well be defined homogeneal, especially since men usually call those things homogeneal, which are so in all qualities that come under their knowledg, though in other qualities that their knowledg extends not to there may possibly be some heterogeneity.

3. Those colors I call simple, or homogeneal, which are exhibited by homogeneal light.

4. And those compound or heterogeneal, which are exhibited by heterogeneal light.

5. Different colors I call not only the more eminent species, red, yellow, green, blew, purple, but all other the minutest gradations; much after the same manner that not only the more eminent degrees in Musick, but all the least gradations are esteemed different sounds.

Propositions.

1. The Sun's light consists of rays differing by indefinite degrees of Refrangibility.

2. Rays which differ in refrangibility, when parted from one another do proportionally differ in the colors which they exhibit. These two Propositions are matter of fact.

3. There are as many simple or homogeneal colors as degrees of refrangibility. For, to every degree of refrangibility belongs a different color, by *Prop.* 2. And that color is simple by *Def.* 1. and 3.

4. Whiteness in all respects like that of the Sun's immediate light and of all the usual objects of our senses cannot be compounded of two simple colors alone. For such a composition must be made by rays that have only two degrees of refrangibility, by *Def.* 1. and 3; and therefore it cannot be like that of the Suns light, by *Prop.* 1; Nor, for the same reason, like that of ordinary white objects.

5. Whiteness

5. Whiteness in all respects like that of the Sun's immediate light cannot be compounded of simple colors without an indefinite variety of them. For to such a composition there are requisite rays indued with all the indefinite degrees of refrangibility, by *Prop.* 1. And those infer as many simple colors, by *Def.* 1. and 3. and *Prop.* 2. and 3.

To make these a little plainer, I have added also the Propositions that follow.

6. The rays of light do not act on one another in passing through the same Medium. This appears by several passages in the *Transactions pag.* 5097, 5098, 5100, and 5101. and is capable of further proof.

7. The rays of light suffer not any change of their qualities from refraction.

8. Nor afterwards from the adjacent quiet *Medium*. These two Propositions are manifest *de facto* in homogeneal light, whose color and refrangibility is not at all changeable either by refraction or by the contermination of a quiet *Medium*. And as for heterogeneal light, it is but an aggregate of several sorts of homogeneal light, no one sort of which suffers any more alteration than if it were alone, because the rays act not on one another, by *Prop.* 6. And therefore the aggregate can suffer none. These two *Propositions* also might be further proved apart by Experiments, too long to be here described.

9. There can no homogeneal colors be educed out of light by refraction which were not commixt in it before: Because, by *Prop.* 7, and 8, Refraction changeth not the qualities of the rays, but only separates those which have divers qualities, by meanes of their different Refrangibility.

10. The Sun's light is an aggregate of an indefinite variety of homogeneal colors; by *Prop.* 1. 3, and 9. And hence it is, that I call homogeneal colors also primitive or original. And thus much concerning Colors.

An Extract of a Letter lately written by an ingenious person from Paris, *containing some Considerations upon* Mr. Newtons *doctrine of Colors, as also upon the effects of the different Refractions of the Rays in Telescopical Glasses.*

I Have seen, how Mr. *Newton* endeavours to maintain his new Theory concerning *Colours*. Me thinks, that the most important Objection, which is made against him by way of *Quaere*, is that, Whether there be more than two sorts of Colours. For my part, I believe, that an *Hypothesis*, that should explain mechanically and by the nature of motion the Colors *Yellow* and *Blew*, would be sufficient for all the rest, in regard that those others, being only more deeply charged (as appears by the Prismes of Mr. *Hook*) do produce the dark or deep-Red and Blew; and that of these four all the other colors may be compounded. Neither do I see, why Mr. *Newton* doth not content himself with the two Colors, Yellow and Blew; for it will be much more easy to find an *Hypothesis* by Motion, that may explicate these two differences, than for so many diversities as there are of others Colors. And till he hath found this *Hypothesis*, he hath not taught us, what it is wherein consists the nature and difference of Colours, but only this accident (which certainly is very considerable,) of their *different Refrangibility*.

As for the composition of *White* made by all the Colors together, it may possibly be, that *Yellow* and *Blew* might also be sufficient for that: Which is worth while to try; and it may be done by the Experiment, which Mr. *Newton* proposeth, by receiving against a wall of a darkn'd room the Colours of the Prisme, and to cast their reflected light upon white paper. Here you must hinder the Colors of the extremities, *viz.* the Red and Purple, from striking against the wall, and leave only the intermediate Colors, yellow, green and blew, to see, whether the light of these alone would not make the paper appear white, as well as when they all give light. I even doubt, whether the lightest place of the yellow color may not alone produce that effect, and I mean to try it at the first conveniency: for this thought never came into my mind but just now.

now. Mean time you may see, that if these Experiments do succeed, it can no more be said, that all the Colors are necessary to compound White, and that 'tis very probable, that all the rest are nothing but degrees of *Yellow* and *Blew*, more or less charged.

Lastly, touching the Effect of the different Refractions of the Rays in Telescopical Glasses, 'tis certain, that Experience agrees not with what Mr. *Newton* holds. For to consider only a picture, which is made by an object-glass of 12 feet in a dark room, we see, it is too distinct and too well defined to be produced by rayes, that should stray the 50*th*. part * of the Aperture. So that, (as I believe I have told you heretofore,) the difference of the Refrangibility doth not, it may be, alwayes follow the same proportion in the great and small inclinations of the Rayes upon the surface of the Glass.

* *Compare herewith what Mr.* Newton *saith in* Numb. [illegible] *of these Tracts, pag.* [illegible].

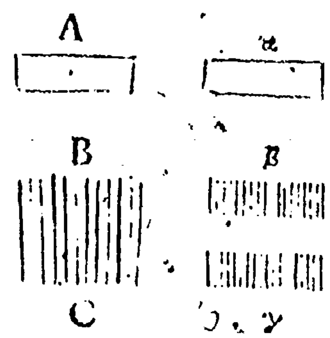
Mr. Newtons *Answer to the foregoing Letter further explaining his Theory of Light and Colors, and particularly that of Whiteness; together with his continued hopes of perfecting Telescopes by Reflections rather than Refractions.*

Concerning the business of Colors; in my saying that when Monsieur *N.* hath shewn how *White* may be produced out of two uncompounded colors, I will tell him, why he can conclude nothing from *that*; my meaning was, that such a White, (were there any such,) would have different properties from the White, which I had respect to, when I described my Theory, that is, from the White of the Sun's immediate light, of the ordinary objects of our senses, and of all white *Phaenomena* that have hitherto faln under my observation. And those different properties would evince it to be of a different constitution: Insomuch that such a production of white would be so far from contradicting, that it would rather illustrate and confirm my Theory; because by the difference of that from other whites it would appear, that other Whites are not compounded of only two colours like that. And therefore if Monsieur *N.* would prove any thing, it is requisite that he do not only produce out of two primitive Colors a white which to the naked eye shall appear like other whites, but also shall agree with them in all other properties.

But to let you understand wherein such a white would differ from other whites and why from thence it would follow that other whites are otherwise compounded, I shall lay down this position.

That a compounded color can be resolved into no more simple colors then those of which it is compounded.

This seems to be self evident, and I have also tryed it several ways, and particularly by this which follows. Let α represent an oblong piece of white paper about ⅓ or ¼ of an inch broad, and illuminated in a dark room with a mixture of two colours cast upon it from two Prisms, suppose a deep blew and scarlet, which must severally be as uncompounded as they can conveniently be made. Then at a convenient distance, suppose of six or eight yards, view it through a clear triangular glass or crystal Prism held parallel to the paper, and you shall see the two colors parted from one another in the fashion of two images of the paper, as they are represented at β and γ, where suppose β the scarlet and γ the blew, without green or any other color between them.



Now from the aforesaid Position I deduce these two conclusions. 1. That if there were found out a way to compound white of two simple colors only, that white would be again resolvable into no more than two. 2. That if other whites (as that of the Suns light, &c. be resolvable into more than two simple colours (as I find by Experiment that they are) then they must be compounded of more than two.

To make this plainer, suppose that A represents a white body illuminated by a direct beam of the Sun transmitted through a small hole into a dark room, and α such another body illuminated by a mixture of two simple colors, which if possible may

may make it also appear of a white color exactly like A. Then at a convenient distance view these two whites through a Prism, and A will be changed into a series of all colors, Red, Yellow, Green, Blew, Purple, with their intermediate degrees succeeding in order from B to C. But α, according to the aforesaid Experiment, will only yield those two colors of which 'twas compounded, and those not conterminate like the colors at BC, but separate from one another as at β and γ, by means of the different refrangibility of the rays to which they belong. And thus by comparing these two whites, they would appear to be of a different constitution, and A to consist of more colors then α. So that what Monsieur N. contends for, would rather advance my Theory by the access of a new kind of white than conclude against it. But I see no hopes of compounding such a white.

As for Monsieur N. his expression, that I maintain my doctrine with some concern, I confess it was a little ungrateful to me to meet with objections which had been answered before, without having the least reason given me why those answers were insufficient. The answers which I speak of are in the Transactions from *pag.* 5093 to *pag.* 5102. And particularly in *pag.* 5095; to shew that there are other simple colors besides blew and yellow, I instance in a simple or homogeneal Green, such as cannot be made by mixing blew and yellow or any other colours: And there also I shew why, supposing that all colors might be produced out of two, yet it would not follow that those two are the only Original colors. The reasons I desire you would compare with what hath been now said of White. And so the necessity of all colors to produce white might have appear'd by the Experiment *pag.* 5097, where I say, that if any color at the *Lens* be intercepted, the whiteness (which is compounded of them all) will be changed into (the result of) the other colors.

However, since there seems to have happened some misunderstanding between us, I shall endeavor to explain my self a little further in these things according to the following method.

Definit.

collect rays at equal distances, he will find how much he is mistaken, and that I have not been extravagant, as he imagins, in preferring Reflexiors. And as for what he says of the difficulty of the praxis, I know it is very difficult, and by those ways which he attempted it I believe it unpracticable. But there is a way insinuated in the *Transactions pag.* 3080. by which it is not improbable but that as much may be done in large Telescopes, as I have thereby done in short ones, but yet not without more then ordinary diligence and curiosity.

A Relation from Dantzick, *about an odd effect of Thunder and Lightning upon Wheat and Rye in the Granaries of that City; communicated in a Letter of* June 24. 1673. *by M.* Christ. Kirkby.

SIR,

YOU doubtless know, how much this City is famed for its numerous and convenient Granaries, it being the Repository of all sorts of grain, the fruitful Kingdom of *Poland* affords. In those Granaries are laid up chiefly Wheat and Rye in parcels, of 20, to 30 and 60 Lasts in one chamber, according to its largeness, and the dryness of the Corn; which they turn over 3, 4, 5, 6 times a week, as need requires to keep it sweet, and fit for shipping. Now it hapned, that about the latter end of *March* and *April* last we had much and violent Thunder and Lightning, which had this unhappy effect upon all the parcels of Wheat and Rye of the last years growth, that, though over-night they were dry, sweet, and fit for shipping, the next morning they had lost all these good qualities, and were become clammy and stinking, and consequently unfit to be ship't away for the present: So that the Owners, if they would not loose their grain, were forced to cause it to be turn'd over two or three times a day, and yet it required six weeks, if not longer, before it was recover'd.

This is a thing, which often happens to Corn that hath not lain in the Granary a whole year, or not swet thoroughly in the straw before it be thrash'd out. An accident little noted, yet in my judgment worth the inquiring into. For, though the Alterations, caused by Thunder in *Liquors*, be taken notice of, and probable reasons given for them; yet I judge this somewhat more abstruse, and therefore more worth while to be consider'd.

A

A Relation of an un-common Case in Physick, communicated by the same from Dantzick *in a Letter of* March 18. 1672/73.

SIR,

I Cannot omit acquainting you with an odd Accident, lately come to my knowledge. A Minister of about 50 years of age, being much indisposed, and often relapsing into a distemper accompanied with vomiting and purging, his Physitian, when I had the opportunity of speaking with him about it, told me, that he was perswaded, that his cure was obstructed by the Patient's being obliged to study: For when by the help of the medicines, prescribed to and used by him, he was brought to a considerable degree of recovery, his studying and preaching made him constantly relapse. This appearing to me some-what strange, that study and discoursing should cast a man into such violent distempers, and the reasons, given by the Doctor for it, not prevailing with me, he one day surprised me by relating what himself had seen, giving the said Minister a visit, which might confirm his conjecture concerning the Spirits being drawn away from the stomach, and leaving the digestive power languid; which vvas, That the Preacher falling into a relapse after a Sermon preached by him, and Vomits comming strongly upon him, he cast out, amongst other matter, several pieces, some as large as the end of a Mans finger, some less. of a substance, to the touch and eye perfectly resembling *Tallow*; four pieces vvhereof vveighed half an ounce. What may be inferred hence for the doctrine of Concoction, I must leave to others to consider.