

PHILOSOPHICAL TRANSACTIONS.

February 19. 1671.

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A Letter of Mr. Isaac Newton, Professor of the Mathematicks in the University of Cambridge; containing his New Theory about Light and Colors: sent by the Author to the Publisher from Cambridge, Febr. 6. 1671; in order to be communicated to the R. Society.

S I R,

TO perform my late promise to you, I shall without further ceremony acquaint you, that in the beginning of the Year 1666 (at which time I applyed my self to the grinding of Optick glasses of other figures than *Spherical*,) I procured me a Triangular glass-Prisme, to try therewith the celebrated *Phænomena* of

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Colours.

Colours. And in order thereto having darkened my chamber, and made a small hole in my window-shuts, to let in a convenient quantity of the Suns light, I placed my *Prisme* at his entrance, that it might be thereby refracted to the opposite wall. It was at first a very pleasing divertisement, to view the vivid and intense colours produced thereby; but after a while applying my self to consider them more circumspectly, I became surpris'd to see them in an *oblong* form; which, according to the received laws of Refraction, I expected should have been *circular*.

They were terminated at the sides with streight lines, but at the ends, the decay of light was so gradual, that it was difficult to determine justly, what was their figure; yet they seem'd *femicircular*.

Comparing the length of this coloured *Spectrum* with its breadth, I found it about five times greater; a disproportion so extravagant, that it excited me to a more then ordinary curiosity of examining, from whence it might proceed. I could scarce think, that the various *Thickness* of the glass, or the termination with shadow or darkness, could have any Influence on light to produce such an effect; yet I thought it not amiss, first to examine those circumstances, and so tryed, what would happen by transmitting light through parts of the glass of divers thickneses, or through holes in the window of divers bignesses, or by setting the *Prisme* without so, that the light might pass through it, and be refracted before it was terminated by the hole: But I found none of those circumstances material. The fashion of the colours was in all these cases the same.

Then I suspected, whether by any *unevenness* in the glass, or other contingent irregularity, these colours might be thus dilated. And to try this, I took another *Prisme* like the former, and so placed it, that the light, passing through them both, might be refracted contrary ways, and so by the latter returned into that course, from which the former had diverted it. For, by this means I thought, the *regular* effects of the first *Prisme* would be destroyed by the second *Prisme*, but the *irregular* ones more augmented, by the multiplicity of refractions. The event was, that the light, which by the first *Prisme* was diffused into an *oblong* form, was by the second reduced into an *orbicular* one with as much regularity, as when it did not at all pass through them. So that, what ever was the cause of that length, 'twas not any contingent irregularity.

I then proceeded to examin more critically, what might be effected by the difference of the incidence of Rays coming from divers parts of the Sun; and to that end, measured the several lines and angles, belonging to the Image. Its distance from the hole or Prisme was 22 foot; its utmost length $13\frac{1}{4}$ inches; its breadth $2\frac{1}{8}$; the diameter of the hole $\frac{1}{4}$ of an inch; the angle, with the Rays, tending towards the middle of the image, made with those lines, in which they would have proceeded without refraction, was 44 deg. 56'. And the vertical Angle of the Prisme, 63 deg. 12'. Also the Refractions on both sides the Prisme, that is, of the Incident, and Emergent Rays, were as near, as I could make them, equal, and consequently about 54 deg. 4'. And the Rays fell perpendicularly upon the wall. Now subducting the diameter of the hole from the length and breadth of the Image, there remains 13 Inches the length, and $2\frac{1}{8}$ the breadth, comprehended by those Rays, which passed through the center of the said hole, and consequently the angle of the hole, which that breadth subtended, was about 31', answerable to the Suns Diameter; but the angle, which its length subtended, was more then five such diameters, namely 2 deg. 49'.

Having made these observations, I first computed from them the refractive power of that glass, and found it measured by the *ratio* of the sines, 20 to 31. And then, by that *ratio*, I computed the Refractions of two Rays flowing from opposite parts of the Sun's *discus*, so as to differ 31' in their obliquity of Incidence, and found, that the emergent Rays should have comprehended an angle of about 31', as they did, before they were incident.

But because this computation was founded on the Hypothesis of the proportionality of the *sines* of Incidence, and Refraction, which though by my own Experience I could not imagine to be so erroneous, as to make that Angle but 31', which in reality was 2 deg. 49'; yet my curiosity caused me again to take my Prisme. And having placed it at my window, as before, I observed, that by turning it a little about its *axis* to and fro, so as to vary its obliquity to the light, more then an angle of 4 or 5 degrees, the Colours were not thereby sensibly translated from their place on the wall, and consequently by that variation of Incidence, the quantity of Refraction was not sensibly varied. By this Experiment therefore, as well as by the former computation, it was evident, that the difference of the Incidence of Rays, flowing from divers

parts of the Sun, could not make them after decussation diverge at a sensibly greater angle, than that at which they before converged; which being, at most, but about 31 or 32 minutes, there still remained some other cause to be found out, from whence it could be 2 degr. 49'.

Then I began to suspect, whether the Rays, after their trajectory through the Prisme, did not move in curve lines, and according to their more or less curvity tend to divers parts of the wall. And it increased my suspicion, when I remembered that I had often seen a Tennis ball, struck with an oblique Racket, describe such a curve line. For, a circular as well as a progressive motion being communicated to it by that stroke, its parts on that side, where the motions conspire, must press and beat the contiguous Air more violently than on the other, and there excite a reluctance and reaction of the Air proportionably greater. And for the same reason, if the Rays of light should possibly be globular bodies, and by their oblique passage out of one medium into another acquire a circulating motion, they ought to feel the greater resistance from the ambient Æther, on that side, where the motions conspire, and thence be continually bowed to the other. But notwithstanding this plausible ground of suspicion, when I came to examine it, I could observe no such curvity in them. And besides (which was enough for my purpose) I observed, that the difference 'twixt the length of the Image, and diameter of the hole, through which the light was transmitted, was proportionable to their distance.

The gradual removal of these suspicions, at length led me to the *Experimentum Crucis*, which was this: I took two boards, and placed one of them close behind the Prisme at the window, so that the light might pass through a small hole, made in it for the purpose, and fall on the other board, which I placed at about 12 feet distance, having first made a small hole in it also, for some of that Incident light to pass through. Then I placed another prisme behind this second board, so that the light, trajected through both the boards, might pass through that also, and be again refracted before it arrived at the wall. This done, I took the first Prisme in my hand, and turned it to and fro slowly about its *Axis*, so much as to make the several parts of the Image, cast on the second board, successively pass through the hole in it, that I might observe to what places on the wall the second Prisme would refract them.

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And I saw by the variation of those places, that the light, tending to that end of the Image, towards which the refraction of the first Prisme was made, did in the second Prisme suffer a Refraction considerably greater then the light tending to the other end. And so the true cause of the length of that Image was detected to be no other, then that *Light* consists of *Rays differently refrangible*, which, without any respect to a difference in their incidence, were, according to their degrees of refrangibility, transmitted towards divers parts of the wall.

When I understood this, I left off my aforesaid Glass works; for I saw, that the perfection of Telescopes was hitherto limited, not so much for want of glasses truly figured according to the prescriptions of Optick Authors, (which all men have hitherto imagined,) as because that Light it self is a *Heterogeneous mixture of differently refrangible Rays*. So that, were a glass so exactly figured, as to collect any one sort of rays into one point, it could not collect those also into the same point, which having the same Incidence upon the same Medium are apt to suffer a different refraction. Nay, I wondered, that seeing the difference of refrangibility was so great, as I found it, Telescopes should arrive to that perfection they are now at. For, measuring the refractions in one of my Prismes, I found, that supposing the common *sine* of Incidence upon one of its planes was 44 parts, the *sine* of refraction of the utmost Rays on the red end of the Colours, made out of the glass into the Air, would be 68 parts, and the *sine* of refraction of the utmost rays on the other end, 69 parts: So that the difference is about a 24th or 25th part of the whole refraction. And consequently, the object-glass of any Telescope cannot collect all the rays, which come from one point of an object, so as to make them convene at its *focus* in less room then in a circular space, whose diameter is the 50th part of the Diameter of its Aperture; which is an irregularity, some hundreds of times greater, then a circularly figured *Lens*, of so small a section as the Object-glasses of long Telescopes are, would cause by the unsuitness of its figure, were Light *uniform*.

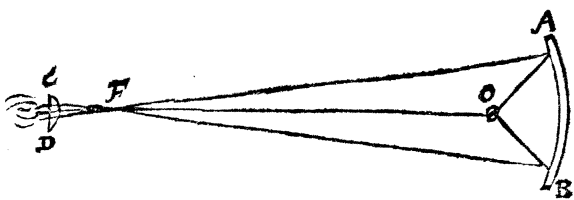
This made me take *Reflections* into consideration, and finding them regular, so that the Angle of Reflection of all sorts of Rays was equal to their Angle of Incidence; I understood, that by their mediation Optick instruments might be brought to any degree of perfection imaginable, provided a *Reflecting* substance could be found,

found, which would polish as finely as Glass, and *reflect* as much light, as glass *transmits*, and the art of communicating to it a *Parabolick* figure be also attained. But there seemed very great difficulties, and I have almost thought them insuperable, when I further considered, that every irregularity in a reflecting superficies makes the rays stray 5 or 6 times more out of their due course, than the like irregularities in a refracting one: So that a much greater curiosity would be here requisite, than in figuring glasses for Refraction.

Amidst these thoughts I was forced from *Cambridge* by the Intervening Plague, and it was more then two years, before I proceeded further. But then having thought on a tender way of polishing, proper for metall, whereby, as I imagined, the figure also would be corrected to the last; I began to try, what might be effected in this kind, and by degrees so far perfected an Instrument (in the essential parts of it like that I sent to *London*,) by which I could discern Jupiters 4 Concomitants, and shewed them divers times to two others of my acquaintance. I could also discern the Moon-like phase of *Venus*, but not very distinctly, nor without some niceness in disposing the Instrument.

From that time I was interrupted till this last Autumn, when I made the other. And as that was sensibly better then the first (especially for Day-Objects,) so I doubt not, but they will be still brought to a much greater perfection by their endeavours, who, as you inform me, are taking care about it at *London*.

I have sometimes thought to make a *Microscope*, which in like manner should have, instead of an Object-glass, a Reflecting piece of metall. And this I hope they will also take into consideration. For those Instruments seem as capable of improvement as *Telescopes*, and perhaps more, because but one reflective piece of metall is requisite in them, as you may perceive by the annexed diagram, where A B representeth the object metall, C D the eye glass, F their common Focus, and O the other focus of the metall, in which the object is placed.



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But to return from this digression, I told you, that Light is not similar, or homogeneous, but consists of *difform* Rays, some of which are more refrangible than others : So that of those, which are alike incident on the same medium, some shall be more refracted than others, and that not by any virtue of the glass, or other external cause, but from a predisposition, which every particular Ray hath to suffer a particular degree of Refraction.

I shall now proceed to acquaint you with another more notable diffimilarity in its Rays, wherein the *Origin of Colours* is unfolded : Concerning which I shall lay down the *Doctrine* first, and then, for its examination, give you an instance or two of the *Experiments*, as a Specimen of the rest.

The Doctrine you will find comprehended and illustrated in the following propositions.

1. As the Rays of light differ in degrees of Refrangibility, so they also differ in their disposition to exhibit this or that particular colour. Colours are not *Qualifications of Light*, derived from Refractions, or Reflections of natural Bodies (as 'tis generally believed,) but *Original* and *connate properties*, which in divers Rays are divers. Some Rays are disposed to exhibit a red colour and no other; some a yellow and no other, some a green and no other, and so of the rest. Nor are there only Rays proper and particular to the more eminent colours, but even to all their intermediate gradations.

2. To the same degree of Refrangibility ever belongs the same colour; and to the same colour ever belongs the same degree of Refrangibility. The *least Refrangible* Rays are all disposed to exhibit a *Red* colour, and contrarily those Rays, which are disposed to exhibit a *Red* colour, are all the least refrangible : So the *most refrangible* Rays are all disposed to exhibit a deep *Violet-Colour*, and contrarily those which are apt to exhibit such a violet colour, are all the most Refrangible. And so to all the intermediate colours in a continued series belong intermediate degrees of refrangibility. And this Analogy 'twixt colours, and refrangibility, is very precise and strict; the Rays always either exactly agreeing in both, or proportionally disagreeing in both.

3. The species of colour, and degree of Refrangibility proper to any particular sort of Rays, is not mutable by Refraction, nor by Reflection from natural bodies, nor by any other cause, that I could yet observe. When any one sort of Rays hath been well parted

parted from those of other kinds, it hath afterwards obstinately retained its colour, notwithstanding my utmost endeavours to change it. I have refracted it with Prismes, and reflected it with Bodies, which in Day-light were of other colours; I have intercepted it with the coloured film of Air interceding two compressed plates of glass; transmitted it through coloured Mediums, and through Mediums irradiated with other sorts of Rays, and diversly terminated it; and yet could never produce any new colour out of it. It would by contracting or dilating become more brisk, or faint, and by the loss of many Rays, in some cases very obscure and dark; but I could never see it changed *in specie*.

Yet seeming transmutations of Colours may be made, where there is any mixture of divers sorts of Rays. For in such mixtures, the component colours appear not, but, by their mutual allaying each other, constitute a midling colour. And therefore, if by refraction, or any other of the aforesaid causes, the difform Rays, latent in such a mixture, be separated, there shall emerge colours different from the colour of the composition. Which colours are not New generated, but only made Apparent by being parted; for if they be again intirely mix't and blended together, they will again compose that colour, which they did before separation. And for the same reason, Transmutations made by the convening of divers colours are not real; for when the difform Rays are again severed, they will exhibit the very same colours, which they did before they entered the composition: as you see, *Blow* and *Yellow* powders, when finely mixed, appear to the naked eye *Green*, and yet the Colours of the Component corpuscles are not thereby really transmuted, but only blended. For, when viewed with a good Microscope, they still appear *Blow* and *Yellow* interspersedly.

5. There are therefore two sorts of Colours. The one original and simple, the other compounded of these. The Original or primary colours are, *Red*, *Yellow*, *Green*, *Blow*, and a *Violet-purple*, together with *Orange*, *Indico*, and an indefinite variety of Intermediate gradations.

6. The same colours in *Specie* with these Primary ones may be also produced by composition: For, a mixture of *Yellow* and *Blow* makes *Green*; of *Red* and *Yellow* makes *Orange*; of *Orange* and *Yellowish green* makes *yellow*. And in general, if any two Colours be mixed, which in the series of those, generated by the Prisme, are

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not too far distant one from another, they by their mutual alloy compound that colour, which in the said series appeareth in the mid-way between them. But those, which are situated at too great a distance, do not so. *Orange* and *Indico* produce not the intermediate *Green*, nor *Scarlet* and *Green* the intermediate *yellow*.

7. But the most surprising and wonderful composition was that of *Whiteness*. There is no one sort of Rays which alone can exhibit this. 'Tis ever compounded, and to its composition are requisite all the aforesaid primary Colours, mixed in a due proportion. I have often with Admiration beheld, that all the Colours of the *Prisme* being made to converge, and thereby to be again mixed as they were in the light before it was Incident upon the *Prisme*, reproduced light, intirely and perfectly white, and not at all sensibly differing from a *direct* Light of the Sun, unless when the glasses, I used, were not sufficiently clear; for then they would a little incline it to *their* colour.

8. Hence therefore it comes to pass, that *Whiteness* is the usual colour of *Light*; for, *Light* is a confused aggregate of Rays indued with all sorts of Colors, as they are promiscuously darted from the various parts of luminous bodies. And of such a confused aggregate, as I said, is generated *Whiteness*, if there be a due proportion of the Ingredients; but if any one predominate, the *Light* must incline to that colour; as it happens in the *Blew* flame of *Brimstone*; the *yellow* flame of a *Candle*; and the various colours of the *Fixed stars*.

9. These things considered, the *manner*, how colours are produced by the *Prisme*, is evident. For, of the Rays, constituting the incident light, since those which differ in Colour proportionally differ in *Refrangibility*, they by their unequal refractions must be severed and dispersed into an oblong form in an orderly succession from the least refracted *Scarlet* to the most refracted *Violet*. And for the same reason it is, that objects, when looked upon through a *Prisme*, appear coloured. For, the difform Rays, by their unequal *Refractions*, are made to diverge towards several parts of the *Retina*, and there express the Images of things coloured, as in the former case they did the *Sun's* Image upon a wall. And by this inequality of refractions they become not only coloured, but also very confused and indistinct.

10. Why the Colours of the *Rainbow* appear in falling drops
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of Rain, is also from hence evident. For, those drops, which refract the Rays, disposed to appear purple, in greatest quantity to the Spectators eye, refract the Rays of other sorts so much less, as to make them pass beside it; and such are the drops on the inside of the *Primary* Bow, and on the outside of the *Secondary* or Exterieur one. So those drops, which refract in greatest plenty the Rays, apt to appear red, toward the Spectators eye, refract those of other sorts so much more, as to make them pass beside it; and such are the drops on the exterior part of the *Primary*, and interior part of the *Secondary* Bow.

11. The odd Phænomena of an infusion of *Lignum Nephriticum*, *Leaf gold*, *Fragments of coloured glass*, and some other transparently coloured bodies, appearing in one position of one colour, and of another in another, are on these grounds no longer riddles. For, those are substances apt to reflect one sort of light and transmit another; as may be seen in a dark room, by illuminating them with similar or uncompounded light. For, then they appear of that colour only, with which they are illuminated, but yet in one position more vivid and luminous than in another, accordingly as they are disposed more or less to reflect or transmit the incident colour.

12. From hence also is manifest the reason of an unexpected Experiment, which Mr. *Hook* somewhere in his *Micrography* relates to have made with two wedg-like transparent vessels, fill'd the one with a red, the other with a blew liquor: namely, that though they were severally transparent enough, yet both together became opaque; For, if one transmitted only red, and the other only blew, no rays could pass through both.

13. I might add more instances of this nature, but I shall conclude with this general one, that the Colours of all natural Bodies have no other origin than this, that they are variously qualified to reflect one sort of light in greater plenty than another. And this I have experimented in a dark Room by illuminating those bodies with uncompounded light of divers colours. For by that means any body may be made to appear of any colour. They have there no appropriate colour, but ever appear of the colour of the light cast upon them, but yet with this difference, that they are most brisk and vivid in the light of their own day-light colour. *Minium* appeareth there of any colour indifferently, with which 'tis illustrated, but yet most luminous in red, and so

Bise appeareth indifferently of any colour with which 'tis illustrated, but yet most luminous in blew. And therefore *Minium* reflecteth Rays of any colour, but most copiously those indued with red; and consequently when illustrated with day-light, that is, with all sorts of Rays promiscuously blended, those qualified with red shall abound most in the reflected light, and by their prevalence cause it to appear of that colour. And for the same reason *Bise*, reflecting blew most copiously, shall appear blew by the excess of those Rays in its reflected light; and the like of other bodies. And that this is the intire and adequate cause of their colours, is manifest, because they have no power to change or alter the colours of any sort of Rays incident apart, but put on all colours indifferently, with which they are inlightened.

These things being so, it can be no longer disputed, whether there be colours in the dark, nor whether they be the qualities of the objects we see, no nor perhaps, whether Light be a Body. For, since Colours are the *qualities* of Light, having its Rays for their intire and immediate subject, how can we think those Rays *qualities* also, unless one quality may be the subject of and sustain another; which in effect is to call it *Substance*. We should not know Bodies for substances, were it not for their sensible qualities, and the Principal of those being now found due to something else, we have as good reason to believe that to be a Substance also.

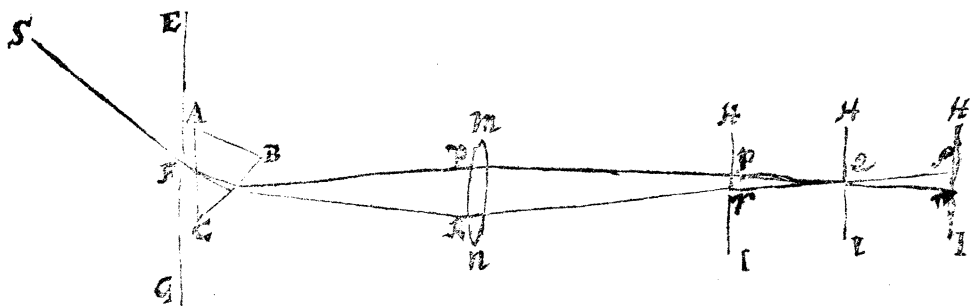
Besides, whoever thought any quality to be a *heterogeneous* aggregate, such as Light is discovered to be. But, to determine more absolutely, what Light is, after what manner refracted, and by what modes or actions it produceth in our minds the Phantasms of Colours, is not so easie. And I shall not mingle conjectures with certainties.

Reviewing what I have written, I see the discourse it self will lead to divers Experiments sufficient for its examination: And therefore I shall not trouble you further, than to describe one of those, which I have already insinuated.

In a darkened Room make a hole in the shut of a window, whose diameter may conveniently be about a third part of an inch, to admit a convenient quantity of the Suns light: And there place a clear and colourless Prisme, to refract the entring light towards the further part of the Room, which, as I said, will thereby be diffused into an oblong coloured Image. Then place a *Lens* of

about three foot radius (suppose a broad Object-glass of a three foot Telescope,) at the distance of about four or five foot from thence, through which all those colours may at once be transmitted, and made by its Refraction to convene at a further distance of about ten or twelve feet. If at that distance you intercept this light with a sheet of white paper, you will see the colours converted into whiteness again by being mingled. But it is requisite, that the *Prisme* and *Lens* be placed steddy, and that the paper, on which the colours are cast, be moved to and fro; for, by such motion, you will not only find, at what distance the whiteness is most perfect, but also see, how the colours gradually convene, and vanish into whiteness, and afterwards having crossed one another in that place where they compound Whiteness, are again dissipated, and severed, and in an inverted order retain the same colours, which they had before they entered the composition. You may also see, that, if any of the Colours at the *Lens* be intercepted, the Whiteness will be changed into the other colours. And therefore, that the composition of whiteness be perfect, care must be taken, that none of the colours fall besides the *Lens*.

In the annexed design of this Experiment, A B C expresseth the Prism set endwise to light, close by the hole F of the window



E G. Its vertical Angle A C B may conveniently be about 60 degrees: M N designeth the *Lens*. Its breadth $2\frac{1}{2}$ or 3 inches. S F one of the straight lines, in which difform Rays may be conceived to flow successively from the Sun. F P, and F R two of those Rays unequally refracted, which the *Lens* makes to converge towards Q, and after decussation to diverge again. And H I the paper, at divers distances, on which the colours are projected: which in Q constitute *Whiteness*, but are *Red* and *Yellow* in R, r, and s, and *Blue* and *Purple* in P, p, and π .

If you proceed further to try the impossibility of changing any uncompounded colour (which I have asserted in the third and thirteenth Propositions,) 'tis requisite that the Room be made very dark, least any scattering light, mixing with the colour, disturb and allay it, and render it compound, contrary to the design of the Experiment. 'Tis also requisite, that there be a perfecter separation of the Colours, than, after the manner above described, can be made by the Refraction of one single Prism, and how to make such further separations, will scarce be difficult to them, that consider the discovered laws of Refractions. But if tryal shall be made with colours not thoroughly separated, there must be allowed changes proportionable to the mixture. Thus if compound Yellow light fall upon Blew *Bise*, the *Bise* will not appear perfectly yellow, but rather green, because there are in the yellow mixture many rays indued with green, and Green being less remote from the usual blew colour of *Bise* than yellow, is the more copiously reflected by it.

In like manner, if any one of the Prismatick colours, suppose Red, be intercepted, on design to try the asserted impossibility of reproducing that Colour out of the others which are pretermitted; 'tis necessary, either that the colours be very well parted before the red be intercepted, or that together with the red the neighbouring colours, into which any red is secretly dispersed, (that is, the yellow, and perhaps green too) be intercepted; or else, that allowance be made for the emerging of so much red out of the yellow green, as may possibly have been diffused, and scatteringly blended in those colours. And if these things be observed, the new Production of Red, or any intercepted colour will be found impossible.

This, I conceive, is enough for an Introduction to Experiments of this kind; which if any of the *R. Society* shall be so curious as to prosecute, I should be very glad to be informed with what success: That, if any thing seem to be defective, or to thwart this relation, I may have an opportunity of giving further direction about it, or of acknowledging my errors, if I have committed any.

So far this Learned and very Ingenious Letter; which having been by that *Illustrious Company*, before whom it was read, with much applause committed to the consideration of some of their Fellows, well versed in this argument, the Reader may possibly in an other *Treat* be informed of some report given in upon this Discourse.

Ar.