Newton's Contributions to Optics

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Newton's epochal work on dynamics and gravitation sometimes tends to eclipse his great contributions to optics. Also, his work in optics is rivalled by equally significant work by his contemporaries, especially Huygens. Yet his creativity is apparent, even in ideas and models in optics that were later abandoned in science.

1. Theory of Colour

Newton's discovery that white light is a mixture of colours now looks so common place that its truly path breaking nature can be appreciated only when it is set in its historical context. Colour has long been an issue of philosophical and scientific debate. Colour is an example of a 'secondary quality', in contrast to a 'primary quality' like size or shape. Does colour reside in the object or in the mind? Some thought it was only an idea, a mental impression, with nothing objective out there. The British empiricist John Locke got it closer to science when he said that colour is both an objective property and an idea; the idea is caused by but does not 'resemble' the objective property (unlike a primary quality in which case it does). In modern terms, the physics of colour (i.e. the nature of its objective property) is one thing; the physiology of colour perception is another.

Around Newton's time, a number of leading figures in science were thinking about the physics of colour. The nature of colour was inseparably linked to the nature of light. The ether was in vogue, as a medium for the propagation of light, though specific models of ether differed from one another. For Rene Descartes, light was an ethereal pulse transmitted instantaneously from a luminous body, much like a quick blow transmitted by a rigid stick. Colour was associated with characteristic rotations of the spherical particles of the ether, which are changed by their

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contacts with the bodies – the more rapidly rotating particles than the usual cause the sensation of red, the slower give rise to blue sensation, and so on. Hooke regarded light as a short vibratory motion in the luminous body, which spreads out symmetrically in the surrounding ether in the form of pulses. Colour in his view is generated when this disturbance is distorted due to refraction. "Blue is an impression on the Retina of an oblique and confus`d pulse of light, whose weakest part precedes, and whose strongest part follows…" For Red, it was supposed to be the other way : the strongest precedes and the weakest follows. Newton found these ideas galling (as we do now). For him, rectilinearity of light meant that light was a radiation of matter – projectile-like particles streaming out of a source; it could not be a pressure or vibratory motion of the ether. But he could not decide if colour was due to speed, momentum or something else of these 'globuli' as he called them then. Fortunately, his great discovery described below did not critically depend on the underlying model of light.

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Newton's earliest foray into the topic of colour was probably in early 1666, when he was a scholar at Trinity College, Cambridge. He aligned a triangular prism in the path of a sunbeam entering a darkened chamber through a small hole in its window shutter. As expected, he saw the colours of the rainbow on the wall vividly. But on examining them more circumspectly, he was surprised. He expected the refracted light to form a circle on the wall, since all the sun's rays would be refracted equally. Instead, he saw an oblong shape – the length of the coloured spectrum was about five times its breadth. He tried with different prisms, different sizes of the hole, besides moving a given prism to vary the thickness of the glass through which the rays passed; yet the oblong shape persisted. Descartes in a similar experiment had missed seeing this, since he had held the screen too close to the prism. Newton correctly guessed that the oblong shape was due to the differential refrangibility of rays of different colours that are all present in the white light.

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But he wished to confirm this insight. In the fine tradition of the

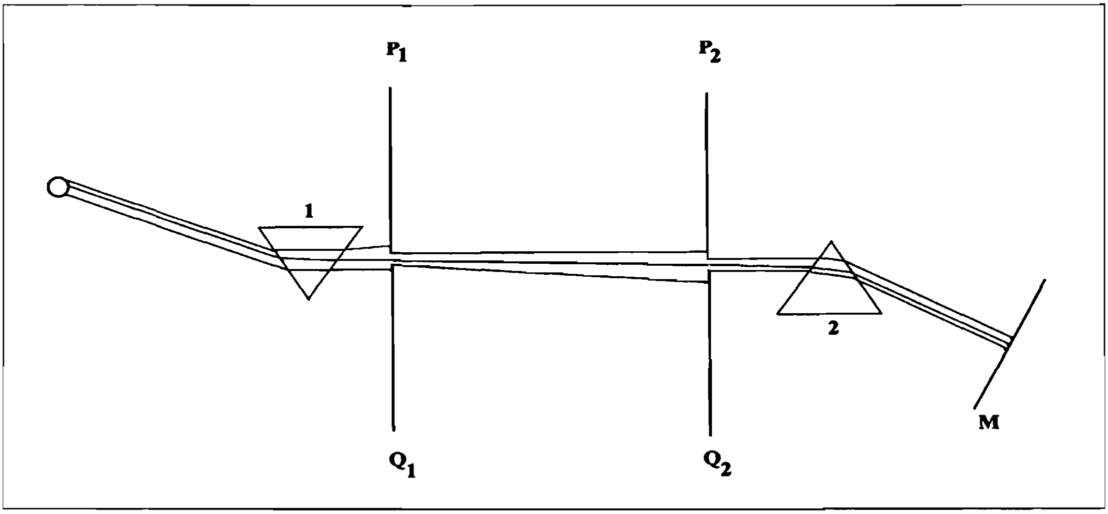

Figure 1. *Newton's 'experimentum crucis' showing that colours are not created by refraction, but exist in white light. The two slits P_1Q_1 and P_2Q_2 are about 4 m apart. Light beam entering through the shutter falls on prism 1. As the prism is rotated axially, pure colours appear in succession at different points on the screen at M.*

scientific methodology as then expounded by Bacon, Newton carried out his famous *experimentum crucis* – the crucial experiment. The key idea was to isolate a beam of coloured light from one prism and send that through another prism. The second prism did not create new colours nor did it alter the colours emerging from the first prism. (*Figure* 1.)

"Colours are not qualifications of Light, ... but original and connate properties", thus concluded Newton. White light is a heterogeneous mixture of different colours – a conception that was just the opposite to Hooke's for whom white light was fundamental and colour its modification. Newton added further experiments in support of his view. In one of them, a lens collected a diverging spectrum of colours and recombined the rays to obtain a white spot on its focus. Beyond the focus, the spectrum reappeared in reversed order of colour. His new theory of colours was published after six years of gestation in 1672 in *Philosophical Transactions*.

2. The Reflecting Telescope

Even as he was thinking about the nature of light and colour, Newton was also perfecting the art of grinding glass and polishing lenses to different non-spherical shapes. Telescope makers

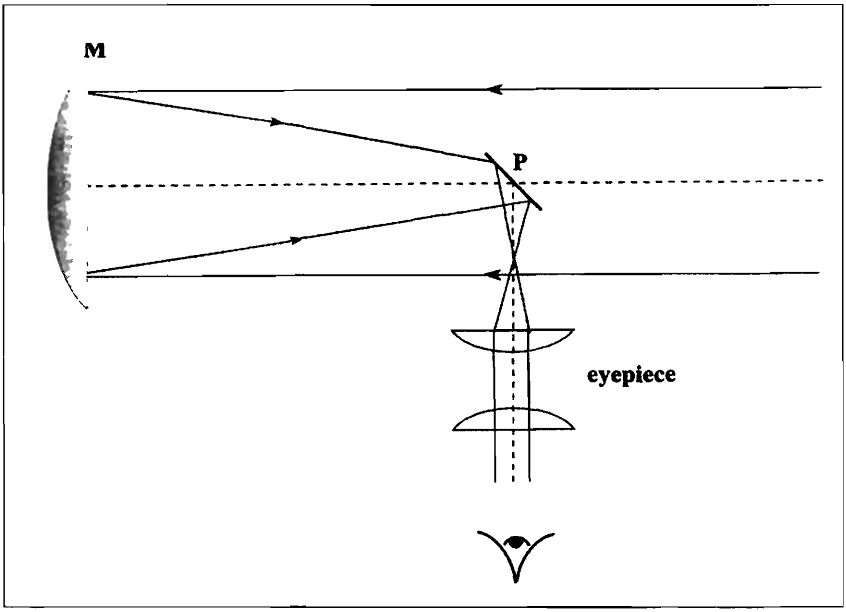

Figure 2. Schematic diagram of Newton's reflecting telescope.

were all too familiar with the imperfections of their instruments – the aberrations. Spherical lenses fail to converge rays of light from an object to a single point. Also the larger the lenses, the more are the unwanted colours, arising from the dispersion of white light, especially from the prism-like edges of the lenses. To eliminate this chromatic aberration, Newton built a new type of telescope that used a reflecting mirror in place of a refracting lens. The bigger the mirror, the more light it would gather. But the technical difficulty of polishing metal to the smoothness of glass was daunting. Using his furnace, Newton cast a tin and copper alloy and refined its surface by grinding it with great care and strength. The first Reflecting Telescope (*Figure* 2) was built with a six inch long tube in 1669, with a magnification of 40. For two years, he kept it for himself, revelling alone in astronomical delights. The Royal Society came to know of his invention in 1671 and urged him to take public credit for it. Soon he became a Fellow of the Royal Society.

3. The Corpuscular Model of Light

Though the corpuscular model of light is (rightly) attributed to him, Newton was very careful not to 'mingle conjectures with certainties'. He used the corpuscular picture as a heuristic aid for his optical experiments and models, but hesitated to elevate it to a certain 'fact' of science, and, in fact, often avoided it in public accounts of his scientific work. Yet, he made valiant attempts to use this picture to provide a rigorous explanation of optical phenomena like reflection, refraction, chromatic dispersion and even diffraction. He was only partially successful.

On first sight, reflection is easily explained in this view. The light corpuscles impinging on a surface reflect, like a ball from a hard surface, satisfying the law of reflection. But when matter is assumed to have discrete (atomic) structure at the micro scale (and Newton regarded corpuscular structure of matter not a conjecture but a certainty), this simple explanation breaks down. Newton considered the reflection of light corpuscles to occur variously – from the ether within the pores of the body, from the corpuscles of the body, from loose particles within the pores, etc. He carried out calculations of momentum change of light corpuscles of different size colliding with particles of different size. He could not quite arrive at a truly satisfactory explanation. Finally, in *Opticks*, he conjectured "some power of a body which is evenly diffused over its surface" – in modern terms, a phenomenological average force!

Regarding refraction, the model predicts that the speed of light corpuscles should be greater in an optically dense medium (index of refraction n >1) than in air. A light corpuscle travelling in air and incident on, say, an air-water interface is attracted by the water molecules. By symmetry, only the normal component of velocity changes, while the parallel component remains unchanged. The resultant direction in the medium thus changes from OA to OB (*Figure* 3). We then have

$$\frac{\sin i}{\sin r} = \frac{OB}{OA} = \frac{v_{water}}{v_{air}} = n \quad (1)$$

Since experimentally, $n > 1$, we have $v_{water} > v_{air}$ (corpuscular model). This, of course, is a wrong result as we now know, but

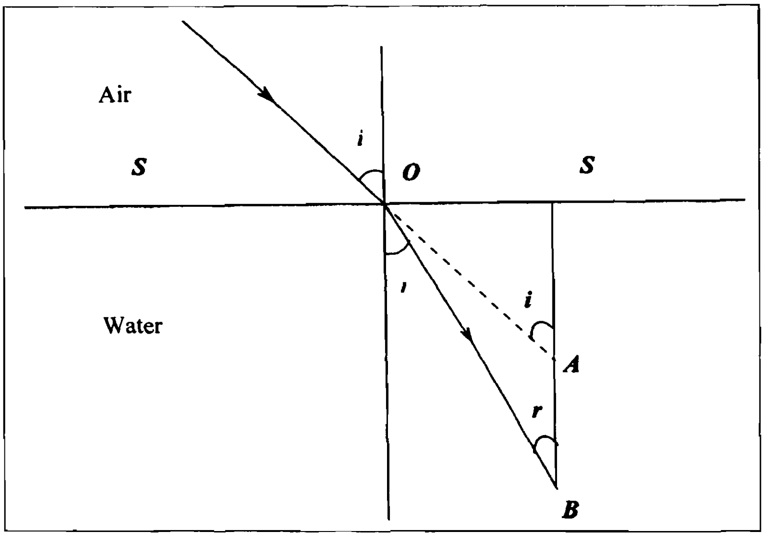

Figure 3. Refraction in the corpuscular model of light.

this was not so obvious at that time, when light velocity measurements were still rudimentary. In a paper to the Royal Society in 1675, Newton explained how such a result could arise in a model of ether. He surmised that, ether is 'rarer' in (optically) denser substances which have narrow pores than it is in free space or air. When a light corpuscle moves through a region of varying ether density, as when it is close to an interface of two media, it is pressed by the denser ether towards the rarer ether, "and receives a continual impulse or ply from that side to recede towards the rarer, & so is accelerated...".

The modern Newtonian concept of force was still some years away. When it arrived in the *Principia*, Newton replaced the ether model by a proper optical mechanical model of refraction. He postulated an intense short-range force between the light corpuscles and the corpuscles of the body. In the small region in which the force acts in a direction normal to the surface, the light corpuscles 'fall', much like the way particles fall under gravity.

Let $f(\rho)$ be the force per unit mass, ρ denoting the perpendicular distance over the interval 0 to R over which the force acts. The tangential (t) component of the velocity is unchanged (*Figure* 4)

$$v_t = v_t^i = \text{constant}. \tag{2}$$

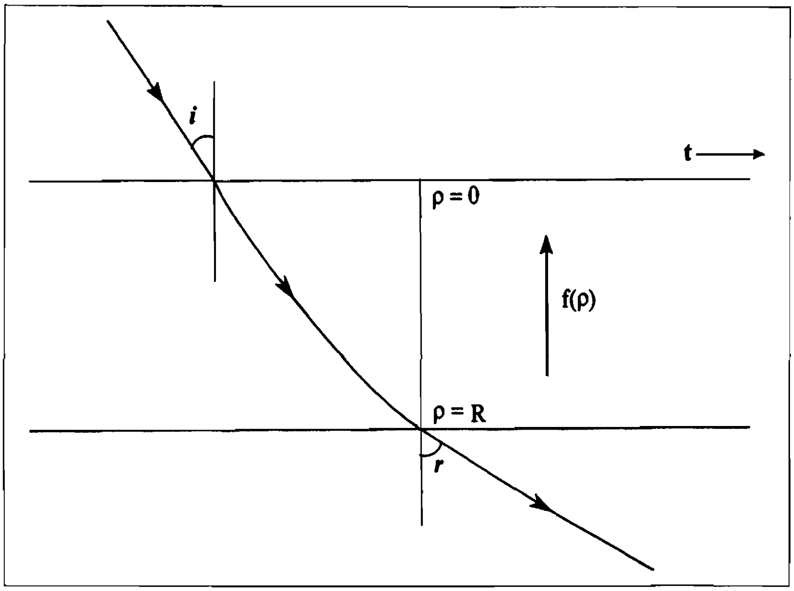

Figure 4. Newton's derivation of Snell's Law of Refraction (the ray shown is from denser to rarer medium).

For the perpendicular component, the equation

$$\frac{d^2\rho}{dt^2} = -f(\rho) \tag{3}$$

upon integration gives

$$v_\rho^{\,2} = (v_\rho^{\,i})^2 - 2\int_0^\rho f(\rho)d\rho\,. \tag{4}$$

The incident speed of the particle is given by

$$(v^i)^2 = (v_t^{\,i})^2 + (v_\rho^{\,i})^2 \tag{5}$$

while the emerging speed of the corpuscle after the effect of the short range force is given by

$$(v^r)^2 = [v_\rho(R)]^2 + (v_t^{\,i})^2 \tag{6}$$

which, using (4) gives

$$(v^r)^2 = (v^i)^2 - 2\phi\,, \tag{7}$$

where

$$\phi = \int_0^R f(\rho)d\rho. \tag{8}$$

Using (1) and (7) we have

$$n = \frac{\sin i}{\sin r} = \frac{v_r}{v_t} = \sqrt{1 - \frac{2\phi}{(v^i)^2}} \tag{9}$$

Now according to his theory of colour, n differed from colour to colour, so the formula showed that the velocity of corpuscles in air varies from one colour to another. This was a testable conclusion, by observing say the colour of the eclipses of Jupiter's moons. When a moon disappears behind the planet, the slowest colour should be seen last, and when it reappears, the fastest colour should be seen first. Newton checked this out with the Royal Astronomer (John Flamsteed) and was disappointed to learn that there was no observational support to this prediction.

The *Principia* digresses to other interesting optical propositions also. For example, Newton solved the following problem: Given two fixed points A and B, find the shape of a refracting surface through a given point C such that all rays emerging from B focus on to A, assuming Snell's Law is true at every point on the surface. The solution is the *'oval of Descartes'* described by the equation $n_1r_1+n_2r_2 = constant$, where n_1 and n_2 are constants and r_1 and r_2 are respectively the distances from the two fixed points.

4. Colour of Thin Films

Hooke's account of colour of thin films in *Micrographia* (1665) had spurred Newton's interest in the subject. Hooke was unable to measure the thickness of such films. Newton's key innovation was to put a convex lens on a flat glass plate and determine the thickness d of the thin film of air by relating it geometrically to the diameter D of the circle ($d=D^2/(8R)$), which could be readily measured. (*Figure* 5.)

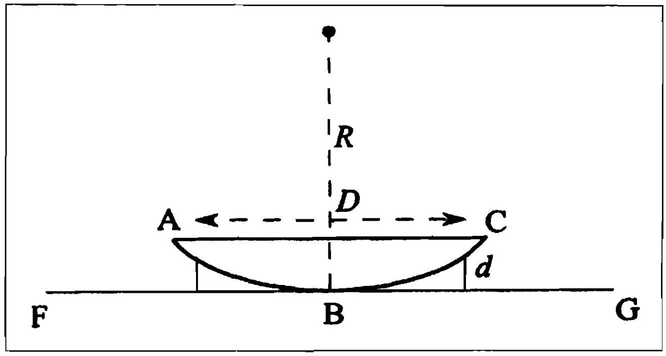

Figure 5. Arrangement for Newton's Rings (Schematic).

When such an arrangement is illuminated and viewed from above, a set of concentric coloured circles ('Newton's Rings') is seen. The circles form an alternating sequence of bright and dark coloured rings, with their common centre – the point of contact – surrounded by a dark spot. Newton also established what Hooke had guessed, that the appearance of colours was periodic. He found that the squares of the diameters of the successive circles increased as integers, i.e. d increases by integral multiples of its value for the first ring:

$$d=m\beta, \tag{10}$$

where m is odd for a bright ring and even for a dark one.

The rings provided a reconfirmation of his recent discovery of the nature of white light. According to this, the colours that were not reflected by the film were transmitted. He confirmed that the transmitted and reflected rings were indeed complementary. He also experimented with monochromatic light of different colours and found that rays of the same colour are reflected at some places and transmitted at others. In the modern wave picture, this follows straight-forwardly from two facts: each colour has a characteristic wave length and the bright and dark rings arise from constructive and destructive interference respectively. For the reflected rings, this interference is between the waves reflected from the surfaces ABC (glass-air interface) and FBG (air-glass interface); β in equation (10) is related to the wavelength λ ($\lambda = 4\beta$). But the periodicity that Newton had found had no natural place in the corpuscular model. So Newton expanded the model to include the ether and its interaction with the corpuscles of light.

Newton assumed that the ether existed and was capable of vibrating. He clarified that light was still corpuscles, not the ethereal vibration, which was simply an effect of light. What then is the origin of periodicity in Newton's rings? His answer was that the vibrating ether reflects light corpuscles at condensations and transmits them at rarefactions. Thus in *Figure* 5, at a certain distance from the centre, the light corpuscle will meet the condensed part of the overtaking vibration and be reflected, giving rise to a bright ring; at double that thickness, it will meet the rarefied part and be transmitted, giving rise to a dark ring, and so on. That is, β in the preceding equation is related to the length of an ethereal vibration. Where is the colour dependence in all this? Well, corpuscles of different colour differ in 'magnitude, strength or rigour' and so excite ethereal vibrations of different size. The red vibrations are larger than the violet ones and so form larger rings!

5. *Opticks*

In *Opticks*, Newton's great work next only to the *Principia*, the ethereal vibrations above were replaced by the notion of the "fits of easy reflections and transmission". The 'fits' were held to be a property of light and not of the ether, a strange fore shadowing of the periodicity of the wave picture, and he used them successfully to deal with the colour of thick plates. *Opticks* published in 1704 is regarded as a classic of experimental science. The main text was a definitive account of optical experiments on refraction, colour and interference and the principles directly emerging from them – work that concerned him in the preceding four decades. Newton freed the main text from conjectures, models and afterthoughts and relegated them all to the Queries. The Queries discussed issues such as the corpuscular model, the cause of colour, fits, double refraction, diffraction, and so on. Some of the Queries are tantalizingly prescient: "The changing of Bodies into Light, and Light into Bodies, is very comfortable to the Course of Nature, which seems delighted with Transmutation", though we should remember that Newton had a passion for alchemy too!

Newton had long been interested to explain what seemed like a challenge to the corpuscular view: diffraction. He assumed that diffraction occurred when light corpuscles pass very close to the edge of the body and are deflected by the short range forces of the particles of the body. Many years before *Opticks*, he had developed a detailed mechanical theory and even derived some laws governing diffraction. But his experiments would not support his diffraction model and he knew it was wrong.

Opticks went through successive editions with some corrections and extensions, particularly to the Queries. The third English edition came out in 1721. Newton had always wished to carry out more optical experiments to revise his diffraction model with the hope of vindicating the corpuscular view of light. But perhaps by then, the powers of the master had declined.

Acknowledgements

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