Essay on Optics

by
Émilie du Châtelet

translated, with notes, by
Bryce Gessell

published by
Project Vox

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This translation is based on the copy of Du Châtelet's *Essai sur l'Optique* located in the Universitätsbibliothek Basel (L I a 755, fo. 230–265). The original essay was transcribed and edited in 2017 by Bryce Gessell, Fritz Nagel, and Andrew Janiak, and published on Project Vox (http://projectvox.org/du-chatelet-1706-1749/texts/essai-sur-loptique).

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EDITOR'S INTRODUCTION TO THE *Essay* AND THE TRANSLATION

The *Essai sur l'optique*

We've known about Émilie du Châtelet's *Essai sur l'optique* for a long time, since she wrote about it in letters to Johann II Bernoulli. Bernoulli visited Du Châtelet's residence at Cirey in March 1739. During the visit, she gave him a copy of her *Essai*, which he took back with him to Basel.

Hundreds of years later, Fritz Nagel discovered that very copy of the *Essai* in the archives at the University of Basel. Dubbed the "Basel manuscript," that text formed the basis for the first-ever published edition of the *Essai sur l'optique*, which was released in October 2017 on Project Vox.

The *Essai* is an important look into Du Châtelet's early views on science and natural philosophy. Drawing inspiration from Newton and others, she reviews many contemporaneous findings on light, and speculates about the laws it obeys. Her use of laws, hypotheses, and other modes of explanation represents her burgeoning interest in the limits of scientific inquiry. Indeed, there are too many things to say about the *Essai* in an introduction like this one; a great deal of work remains to be done with it, on both the text and its content.

For the first analysis of the scientific and philosophical content of the *Essai*, as well as substantial background information and quotations from Du Châtelet's other works and correspondence, see Bryce Gessell, "'Mon petit essai': Émilie du Châtelet's *Essai sur l'optique* and her Early Natural Philosophy," forthcoming in *British Journal for the History of Philosophy*.

For the account of Nagel's discovery and its importance, see his book chapter "'Sancti Bernoulli Orate Pro Nobis': Émilie du Châtelet's Rediscovered *Essai sur l'optique* and her Relation to the Mathematicians from Basel," in *Émilie du Châtelet: between Leibniz and Newton*, 97–112 (edited by Ruth Hagengruber, Springer, 2012).

Translating the *Essai*

Du Châtelet's French prose is almost always clear and well-organized, and she writes with the precision of a scientist. I have tried to bring out this lucid style in my translation.

The work of translating the *Essai* was done concurrently with that of editing the original French text, and so a draft translation has been available since the end of 2017. Since then, I've revised the English version several more times. The translation has also benefited

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from comments by my collaborators Andrew Janiak and Fritz Nagel, and especially from comments by Sandrine Bergès, who served as an external reviewer for the translation.

From the beginning, the prospect of teaching the *Essai* in undergraduate classrooms motivated me to carry out the translation. My early modern philosophy students consistently report that Du Châtelet is one of their favorite figures to discuss. Having an English *Essay on Optics*, together with recent translations of other work by Du Châtelet, makes it possible to present a much broader picture of her thought to a much broader audience.

I'd like to thank all those who have helped with the translation, including those who commented on it and those who have helped publish it as part of the Project Vox team. A particular thank-you to Liz Crisenbery and Liz Milewicz, for their patience in shepherding the text all the way through.

And of course, the most special thanks of all to my wife, my children, and Cookout, who—in that order—have always been there for me.

Bryce Gessell
April 8, 2019
Durham, North Carolina

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Essay on Optics

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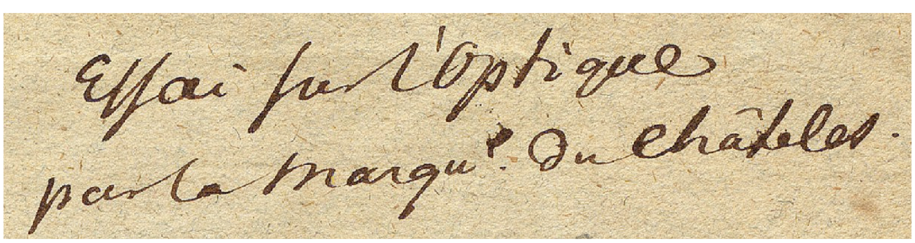
Émilie du Châtelet



Essay on Optics
Introduction

[230r] All areas of physics owe a great deal to Mr. Newton, but there is none he extended more than optics; it may be said that he created and perfected the part of this science of which colors are the object.

Truth is one[1]—and once it is discovered, there is nothing to do but follow it. Thus I dare say that anyone wishing to explain the nature of light and colors, without conforming to Newton's discoveries, will simply go astray.[2] Indeed, the more one wishes to deepen the causes of opacity and transparence, the more one ought to study the treatise on optics from that great man.[3]

Division of the work

Since the transmission or interruption of light is what makes bodies transparent or opaque, and since all opaque bodies reflect some color, I shall divide this essay into four chapters. In the first I shall speak of light, and in the second I shall investigate why transparent bodies transmit it and break it. I shall try in the third to expand on why opaque bodies interrupt it and reflect it. Finally, in the fourth, I shall discuss the cause [230v] of bodies' different colors.

[1] *La verité est une*

[2] **This holds even though Du Fay's experiments led him to believe that there are only three primitive colors, instead of the seven which Newton's experiments had found. Note that it was only in following Newton's discoveries, however, that Du Fay was able to make his—if indeed they are real—and so what I say here is no less true.** (Bold text in footnotes like this one indicates that the note is Du Châtelet's and belongs to the *Essay*; other notes appear in regular print.)

[3] Du Châtelet is referring to Newton's *Opticks*, first published in English in 1704. The second edition appeared in 1718 with substantial changes, especially to the "Queries" at the end of the book (referred to below as "Q 1," "Q 2," and so on). Du Châtelet had access to this text in a French edition called *Traité d'optique* (Paris, 1722), translated by Pierre Coste and based on the second English edition. Many of the experimental results, claims, and speculations Du Châtelet reports in her *Essay* come, with varying degrees of modification, from the *Opticks*.

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Essay on Optics
Chapter 1: On Light

[231^{r}] If, in this work, I wished to examine the nature of light, I would go beyond the limits of my subject. Thus I shall be content to suppose the following truths, as being unanimously accepted by all natural philosophers today.

Accepted views on light

First: light is nothing other than one of the properties of the being, whatever it may be, that we call fire. Fire gives us the sensation of light whenever it is transmitted in a right line[4] to our eyes, in a quantity sufficient to excite them.

Second: light emanates from luminous bodies, and it reaches us from the sun in about seven or eight minutes.

Third: the parts of light, whatever its nature, are so small that we cannot discover their size.

Fourth: what we call a "ray of light" is a beam of seven species of different rays: red, yellow, orange, green, blue, indigo, and violet.[5]

Allow me to pause here for a moment to consider the immense progress that physics has made in Europe in the last eighty years or so.

[231^{v}] The ancients were familiar with the seven colors because they had prisms.[6] They used to say, however, that there wasn't any color in the prisms—rather, there was an appearance of color. "It is clear that no color is created, but only the semblance of a counterfeit color," said Seneca in speaking of the prism.[7]

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[4] Here and below, "in a right line" translates the French *en ligne droite*.

[5] **See note 2 on page 7.**

[6] In this chapter, the Basel manuscript lacks several marginal notes present in both the Paris I and Paris II manuscripts. In addition to the three notes included in the text above, both Paris I and Paris II have notes indicating "the opinion of Seneca and of antiquity regarding the image of the prism," "refutation of this explanation" (referring to Descartes's account of light), and "discovery of Huygens and Rømer on the progression of light." Paris I adds an additional note, written in Du Châtelet's hand, reading "discovery of Newton regarding colors."

[7] In Latin, *apparet non fieri ullum colorem sed speciem falsi coloris*. Du Châtelet is quoting from Seneca's *Quaestiones Naturales*, or "Natural Questions." The passage comes from book I, chapter 7, paragraph 2. For this translation, see *Seneca: Natural Questions*, page 152 (translated by Harry M. Hine, University of Chicago Press, 2010).

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Aristotle's definition of light

Aristotle, who for so long enjoyed a universal monarchy over the sciences, thought that light was an accident. He defined it this way: "The activity of a transparent body qua transparent body." He defined colors as well, as "that which sets in motion a body which is actually transparent."[8] This unintelligible jargon is what people took as the truth for more than two thousand years.

Descartes's explanation of the nature of light

Descartes was the first to dare overthrow these ideas, but he seems to have destroyed Aristotle's world merely to have the pleasure of creating his own. He therefore created light and made certain it was composed of small globules spread out everywhere.[9] These globules had only to be pressed to give us the sensation of light, and only had to turn (or even have a tendency to turn) to make us see colors.[10]

This is not the place to refute this globular pressure of which Descartes made light consist. But from among the throng of arguments which destroy his view, I hope you'll allow me to relate one which seems all the more convincing because our daily experience

[8] Du Châtelet is quoting from Aristotle's *De Anima*, or "On the Soul." The passages are found at 418b9–10 and 418b1–2, respectively, and read in Greek as follows: Φῶς δέ ἐστιν ἡ τούτου ἐνέργεια, τοῦ διαφανοῦς ᾗ διαφανές (418b9–10); Πᾶν δὲ χρῶμα κινητικόν ἐστι τοῦ κατ᾽ ἐνέργειαν διαφανοῦς (418b1–2). The phrase "actually transparent" translates the French *actuellement transparent*. The French word *actuellement* does not usually mean the English "actually," but rather "presently, at the current time." French translations of Aristotle, however, customarily use *actuellement* for Aristotle's technical term κατ᾽ ἐνέργειαν.

[9] Du Châtelet's remark on Descartes "creating a world" refers to a passage from an early work of Descartes's that was not published until after his death—*Le Monde*, or "The World." Here Descartes gives explanations for many natural phenomena but emphasizes that he is not necessarily describing the actual world: "For a while, then, allow your thought to wander beyond this world to view another world—a wholly new one which I shall bring into being before your mind in imaginary spaces...we are taking the liberty of fashioning this matter as we fancy" (*The Philosophical Writings of Descartes*, volume I, page 90, translated by John Cottingham, Robert Stoothoff, and Dugald Murdoch, Cambridge University Press, 1985). Since Descartes later said similar things in his *Principles of Philosophy*, the criticism that he merely "created his own world" was common in Du Châtelet's day. Voltaire, for example, wrote that Descartes "invented new Elements, he created a World; he made Man according to his own Fancy" (*Letters concerning the English Nation*, page 119, London, 1733), and five years later made a similar criticism in his *Elémens de la philosophie de Neuton* (pages ix–x, London, 1738). In a May 1741 review of Du Châtelet's *Insitutions de physique*, the *Journal de Trévoux* said that "this was the fantasy of Descartes...of making a world" (915). Descartes's contemporary, Blaise Pascal, had reached a similar conclusion in his *Pensées*: "Descartes. It has to be said in general: 'That is done by figure and movement', because it is true. But it is absurd to say which or to invent the machine, because that is useless, uncertain, and difficult" (118).

[10] Descartes wrote extensively on light. His view appears in book III, paragraph 55 of *Principles of Philosophy*, where he says that light consists of "the force by means of which the globules of the second element...strive to move away from their centers of motion." But see also his *Optics* (called the *Dioptrics*), where he explains the sine law of refraction, as well as passages from the *Meteorology* and elsewhere.

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sets it continually before our eyes.

[232^r] If light consisted of a pressure on universally-diffused globules, it would not be propagated in a right line. Rather, upon encountering the least obstacle, it would scatter in waves to the right and left, just like all fluids do when passing around obstacles they meet. Therefore since light does not go around bodies—that is, since it is propagated in a right line—it does not consist of a fluid diffused throughout the universe nor in a simple pressure on that imaginary fluid.[11]

Descartes's explanation for the nature of light was therefore neither more true nor better proved than the one it replaced, Aristotle's "activity of a transparent body." One can't help but admit that the only benefit we've drawn from the works of Descartes, great man though he was, is learning how to make mistakes with our method.

At last there arrived a philosopher who, instead of wanting to guess what light is, sought simply to discover its effects by experiment. It is well known that Newton brought the discernment of his mind and the precision of his hand to anatomize this being, whose nature remains unknown.

From the observations [232^v] of Huygens and Rømer on the immersions and emersions of Jupiter's moons, it was known before Newton that light is neither an accident nor a universally-diffused fluid nor a simple pressure on globules. Rather, it was known that it really does move; that its propagation is not instantaneous; and that the sun transmits it to us in seven or eight minutes, as I said on page 8.[12]

But Newton discovered, and later demonstrated, that colors are not caused by a turning of globules nor by a mere modification of bodies. Instead, he showed that all colors in nature are formed from a mixture of seven unalterable, color-producing rays;[13] the prism makes them visible, and all are contained in light. Newton also demonstrated that a single species of these rays gives us the sensation of red without ever being able, by any possible modifications, to give us the sensation of another color. He showed that the same is true for rays producing yellow and for other colors too, and that all these rays mixed together in an equal quantity produce the color white.

Thus did this philosopher succeed in decomposing light. One can say that light is, at the same time, the being which we've investigated most deeply, and the one whose intimate nature is perhaps still the most unknown.

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[11] Du Châtelet's criticism is similar to Newton's in Q 28 of the *Opticks*.

[12] For the work of Huygens and Rømer, see Olivier Darrigol's *A History of Optics*, pages 64–67 (Oxford University Press, 2012).

[13] *du mélange des sept rayons colorifiques et inaltérables*. Newton coined the term "colorific" to describe the tendency of rays to produce certain perceptual experiences of colors, in recognition of the fact that the rays themselves are not colored; see, for example, his *Opticks*, page 120: "in this Composition of white the several Rays do not suffer any Change in their colorific qualities by acting upon one another." Pierre Coste translated "colorific" as *colorifique*. In sections 16 and 17 of the *Essay*, Du Châtelet also speaks of "yellow-producing rays" (*rayons producteurs du jaune*).

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Essay on Optics
Chapter 2:
On Transparent Bodies, and on the Causes of Transparence

Section 1

Light is not visible by itself

[233^r] The particles which make up light are not visible by themselves—we don't see, for example, the luminous cone melting gold in the focus of a burning-glass, unless some opaque body, like smoke, marks out its boundaries for us. Even then it's not the luminous body we see but the opaque body surrounding it, despite the rays being very dense and very clustered within the cone. Thus we do not see light, but by its means we see the bodies which reflect it back to us. Opacity and transparency depend, therefore, on how bodies act on the light they receive.

Section 2

Definitions

The effects of bodies on light can be reduced to four:

1. they transmit it;
2. they break or refract it;[14]
3. they interrupt or extinguish it;
4. they reflect it.

Transparent bodies transmit and refract [233^v] light, and opaque bodies reflect and interrupt it by absorbing it into their substance.

[14] Du Châtelet sometimes uses the French *rompre*, "break," to refer to refraction.

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On the transmission of a perpendicular ray

The mere transmission of light—without refracting, accelerating, or slowing its motion—would not, strictly speaking, be an action of bodies on it. So pure space, or some medium as homogeneous and as continuous as that (if there could be such a thing), would transmit light to us, whether oblique or perpendicular, without acting on it. But we know of no body which neither slows nor accelerates the motion of light when transmitting it.

This acceleration or retardation of motion doesn't bring about any break in a perpendicular ray, but does so necessarily in an oblique ray. For given that oblique motion is composite motion, if one of the two motions into which the composite may be resolved diminishes or increases, the path of the moving object must necessarily be changed. In such a case, light follows the laws which all moving objects follow.

This breaking of an oblique ray is called the "refraction" of light.

Even though all oblique light gets refracted, we still use just the single word "transmission" in speaking of both oblique and perpendicular light. We do so to avoid the confusion which too many distinctions would introduce into our terminology.

Section 3

The size of pores doesn't bring about transparence

It is above all in deepening the mysteries of light that one notices how what is likely is sometimes far from what is true. What's more likely, for example, than thinking that as a body's pores become larger [234*r*] and more numerous, it transmits more light to us? The experiments of the microscope have proven, however, that it cannot be for lack of pores that bodies which don't transmit light oppose its passage. For these instruments have uncovered for us millions of pores in even the most opaque bodies, which would be more than enough to give passage to light.

Proofs

Furthermore, rays are transmitted at the point of contact between two glasses, and if the first of these glasses were adjacent to the air instead of sitting on top of the second, it would reflect many rays from near the surface adjacent to the air. On the other hand, however, the glass transmitting the light has fewer pores than the air reflecting it. Therefore it isn't the quantity of pores which brings about transmission.

But not only is it not for lack of pores that opaque bodies don't transmit light; it is not either the pore size in transparent bodies which causes them to transmit it. Newton showed that, far from bringing it about, pore size opposes the transmission of light.

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A very common experiment is a proof of this surprising truth. An oiled paper, which transmits the light that a dry paper blocks, certainly has smaller pores than it did before they were filled with oil. Pulverized glass (which becomes opaque), wet salt (which becomes transparent), and a thousand other experiments that I won't relate here confirm this discovery.

One could even believe, perhaps, that the straightness of the pores in bodies isn't necessary to their transparency. For the arrangement of pores in a wet paper doesn't seem [234^v] to differ from the pore arrangement in dry paper, even though the latter blocks light and the former transmits it.

Beyond that, how can it happen that water—whose parts are so inclined to motion—nevertheless always maintains a consistent straightness in its pore arrangement, and is so transparent; while a very fine piece of muslin or a very thin paper are opaque, supposedly because their pores are not straight?

We must, therefore, seek some cause for transparency other than the porous nature of bodies and the arrangement of their pores. This arrangement by itself is not enough for transparency, since one can manage to change bodies from opaque to transparent by filling their pores, and likely without changing their orientation.

Section 4

The most homogeneous bodies are the most transparent

We all know that when light passes obliquely from one transparent medium into another, it gets diverted from its path. It gets diverted more as the density of the medium it travels into differs more and more from the one it leaves.

Thus light is broken more when passing from air into glass than from air into water, because the difference between the densities of air and glass is greater than that between the densities of air and water.

Now since light always gets diverted from its path when traveling through media of different densities, the most homogeneous body will be the most transparent: it will transmit more rays in a right line, as it becomes more homogeneous. But take a case where the layers composing any body whatever are of different densities. Because light is always being diverted in different directions upon passing through them, its motion will be absorbed among all the direction shifts it undergoes between these heterogeneous layers. Thus no part of the light [235^r] will be able to make it through such a body in a right line to our eyes, and the body will be opaque. In this way, in order for a body to be transparent, the plates of matter which compose it—as well as the medium existing among its pores—must be of a more or less equal density. When that happens, the ray will be transmitted through the body in a right line.

The oiled-paper experiment I mentioned earlier clearly proves that the density of the

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matter existing among the pores of bodies brings about opacity or transparency. It does so as this matter differs more or less from the density of these surrounding bodies. In this experiment, the oil comes closer than air does to the density of paper. It is for this reason that, in the interior of the paper, light no longer undergoes the refractions and reflections[15] it once did; that is, before the oil flooded its pores and it became permeable to light.

Reasons for the opacity of mercury, despite its fluidity

One of the reasons preventing mercury from being transparent despite its fluidity is probably the density of its parts. Though they are quite fine, because these parts are so compact their density differs greatly from that of the matter among their pores. The difference is too great, in fact, for light to be able to return directly to our eyes from between the parts.

Section 5

All transparent bodies reflect at least some rays

There is no perfectly transparent medium other than pure space, because it alone could transmit all the rays it receives without reflecting any of them or absorbing some into its substance. For all transparent bodies always absorb or [235*v*] reflect some portion of the light they receive.

Now since the different density of contiguous media is the cause of reflection and refraction, and since transparent bodies are surrounded by air, a portion of the rays falling on such bodies is reflected from near the surfaces touching the air (see note 15 on page 14). Thus all light which transparent bodies send back to us returns to our eyes from near their surface, and no perceptible reflection nor refraction takes place in the interior of these bodies. This seems to suggest that the matter running through their pores is denser than air, in contrast to the matter separating the parts of opaque bodies (see also chapter 4, section 13).

If some refraction or reflection did occur on the inside of transparent bodies, they would become hazy—just like what happens to water which is no longer see-through when you disturb it. With water, the movement always mixes into it some foreign bodies which interrupt the transmission of rays. Thus when water falls from some height it stops being transparent in the pool it lands in, because while it falls a great number of air bubbles mix into it. Since this air differs in density from water, it causes a portion of the rays which were transmitted to be reflected.

[15] **The different density of contiguous media brings about both the reflection and refraction of light, just as I intend to explain in the third chapter, section 4.**

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And so when glass is completely transparent, we have to use our hands to check whether the space it occupies is empty or not. We see it only to the extent that surrounding bodies mark out its boundaries for us. But when several pieces of this same glass are set on top of each other, they are no longer transparent. For since the contact among the pieces can [236^r] never be perfect, the air which slips between them interrupts almost entirely the transmission of light.

Section 6

Bodies act on light from afar

Bodies act on light, since they force it to take a new path in refraction and reflection. They also make it lose its motion by absorbing it into their substance (see section 4, chapter 2). But in addition to all these effects which bodies have on the light which reaches them, they exercise still another action on it *before* it has arrived at their first surface.

Impulsion is scarcely conceived better than attraction

All the effects which bodies have on light are similarly incomprehensible. We do believe, however, that we can better conceive of the effects they produce in light which reaches them than we can of the effects produced from afar. Anything having the appearance of a push seems easier to conceive than effects at a distance. But if we examine these ideas rigorously, we may find that we can conceive hardly better of how a body can communicate its motion to another by pushing it than we can of how a body can act on another without touching it. The principle behind both these effects is hidden from us. Impulsion falls more within our ken, but our mind may have no clearer idea of it.

Whether one conceives of it or not, surely we're forced to admit that bodies act on light before it has reached their first surface. It is certain that the glass FF in figure 1—which forces ray CD to divert from its path and to curve toward the perpendicular ER upon crossing it—acts on the ray before it gets to its first surface.[16] Without doubt the ray [236^v] begins refracting at point B, as soon as it enters into the body's sphere of activity.

Refraction begins before the ray has arrived at the first surface of a transparent body

This power which diverts ray CD from its path, and which forces it to curve while approaching glass FF, increases as the ray comes closer to the body. The power also

[16] See appendix 1 for the figures accompanying the text. Du Châtelet's figures resemble others in work by Newton and Pieter van Musschenbroek; see appendices 3 and 4 for their figures and discussion.

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makes itself felt more when FF is denser, so that the refracting force of bodies is nearly proportional to their quantity of matter (if you leave out sulphurous bodies, that is).

It's not only in refracting rays that bodies act on light from a distance. Both transparent and opaque bodies force the rays, or at least all those passing close enough to their edges to be in their sphere of activity, to bend and to curve toward them. Those which pass closest are those which curve the most. You observe this effect in a camera obscura, when you put a knife blade or some other thin body right up to the hole where the light passes through. This is what we call the "inflection" of light.

These effects prove an attraction between bodies and light

When you consider all these effects carefully, it's impossible not to acknowledge an attraction between bodies and light.

This attraction seems, in several cases, to follow laws other than those which bodies follow in acting on each other.

What are the laws of this attraction?

1. The prism experiments show us that rays resist the action of bodies in different ways, and this is what we call the "refrangibility" of light. Yet it does seem difficult to determine by what law violet rays are always the farthest diverted from their path, while red rays get diverted least. [237^r] For since all the different sorts of rays emanate from the sun at the same time, it cannot be because of differential velocity that they resist the action of bodies to a greater or lesser degree. Furthermore, it would be quite bold to attribute their variable resistance to differential mass, since whether fire weighs anything is still undecided.

2. Sulphurous bodies act on light in a greater proportion than you'd expect, given their mass.

3. Finally, the attraction of bodies on each other is imperceptible, and superseded by the earth's attraction on them, unless they are at the point of contact. In contrast, the attraction of bodies on light is very noticeable, even before contact—this is what we see in the case of bending light. And so it seems that the attraction of bodies on light is not entirely bound to the laws which attraction follows among bodies we're familiar with. We know that, among bodies, attraction is always proportional to the masses involved, that it decreases by the square of the distance, and so on. But is it impossible for it to observe other proportions in some circumstances? This is what we cannot determine, I think, without temerity.

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These laws are not known with certainty

Light seems a being apart, unlike any other we're familiar with.[17] I would see no contradiction in supposing that for light there are, in certain circumstances, other laws of attraction than for bodies. There are so many laws for motion produced by impulsion; why couldn't there be a few for motion produced by attraction? In this matter I see neither impossibility nor contradiction in accepting whatever the phenomena might reveal to us.

Attraction observes different proportions [237^v] in contact and at a distance; there could likewise be a special law of attraction between light and bodies.[18] Therefore let us follow the phenomena and see to what extent the laws of attraction among bodies apply to light.

Section 7

How attraction produces refraction

It's already certain that the attraction of bodies on light exists,[19] and that for the majority of bodies that attraction is proportional to their mass.

Since this principle acts on light, it must influence all the effects which bodies produce in it. I shall try to show how the refraction of light can be deduced from them.

1. The attraction of the media which light passes through is what diverts rays from their path, and it diverts them even more as the media differ more in density. This is why light always changes direction toward the medium with the greater attraction. Thus the most homogeneous bodies are the most transparent—since a ray is attracted equally on all sides by the homogeneous particles of such a body, it travels through it without being diverted from its path and without any interruptions in its transmission.

[17] *La lumière paraît un être à part, qui n'est analogue à aucun de ceux que nous connaissons*. Du Châtelet described light and fire as "beings apart" elsewhere as well; see, for example, her 1738 *Dissertation sur la nature et la propagation du feu*: "Fire is a being apart, which is not always subject to the rules which bodies follow...Fire is a being of which we hardly know some attributes, but whose intimate nature is unknown to us, and it is not analogous to any of those which seem more subject than fire to our investigations" (pages 148 and 164). In her errata to the *Dissertation*, Du Châtelet corrected the first part of this passage to say that fire *seems* to be "a being apart."

[18] *et il pourrait bien y avoir aussi, une loi d'attraction particulière entre la lumière et les corps*

[19] The marginal note above is written by Du Châtelet herself, and originally read, "How attraction is the cause of refraction." Du Châtelet also struck out a marginal note a few paragraphs later which reads, "It is attraction which is the cause of refraction." Both the Paris I and Paris II manuscripts retain this latter marginal note.

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Proofs

2. Every light ray traveling through a transparent body obliquely must be thought of—while it passes through—as being moved by two forces, which it obeys at the same time. So while passing through transparent body AB, ray CD in figure 2 obeys the force which would have carried it to E if it hadn't run into AB; but it also obeys the force which AB's attraction impresses on it. We mark this latter force with the line LM, [238^r] for attraction always acts perpendicularly. Thus by the laws of motion, upon obeying these two forces the ray must follow the diagonal LO of the parallelogram LMOE.

If the medium the ray is passing through is denser than the one it is leaving, this diagonal will be as in figure 2—that is, nearer to the perpendicular than the line DE which it would have followed had it not encountered this new medium. For in this case the attraction of the medium works along with the vertical motion of the light and increases it as a result.

But if the medium the light penetrates is less dense than the one it leaves, the diagonal LO described by the ray will be as in figure 3, farther from the perpendicular than line DE. This is because, in this second case, the ray's vertical velocity is diminished by the attraction from the medium it is leaving, which is stronger than that of the medium it is entering. Here this attraction draws it from the perpendicular upward in the direction of ML.

This will be further explained and confirmed by other things I have to say about the subject.

Section 8

It seems that because they didn't know about attraction, this active principle in nature, Descartes and Fermat ended up fighting so intensely (and so pointlessly) over the cause of light's refraction.

Digression on the dispute between Fermat and Descartes over refraction

This argument split the learned world for a long time. Likewise in our day, De Mairan has made it so famous by the care he took to report it (Académie des Sciences 1723)[20] that I think I have to stop briefly to show how, in my opinion, Newton's principles would have ended this argument [238^v] if they had been known in the time of Descartes and his adversary.

[20] Du Châtelet is referring to De Mairan's "Suite des recherches physico-mathématiques sur la réflexion des corps," available in the *Histoire de l'Académie Royale des Sciences Année M. DCCXXIII*, page 532 (Paris, 1753).

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Take a right triangle, and let its hypotenuse represent the oblique incidence of a moving object over a horizontal plane; the line perpendicular to this plane represents the variable vertical velocity, and the line parallel to it represents the constant horizontal velocity. Given these circumstances, by the theory of composite motions we know that when the vertical velocity is slowed or diminished, the angle of the hypotenuse with it must necessarily become greater—or, what amounts to the same thing, the hypotenuse which forms the path of the object must move farther from the line perpendicular to the plane. That line, as I've just said, is the vertical velocity. In contrast, the hypotenuse gets closer to this perpendicular line, and makes a smaller angle with it, when the object's vertical velocity is increased (or slowed less, for the latter produces the same effect as the former).

Now consider the case of passing from one medium into another. As the moving object approaches the perpendicular, its vertical velocity must as a result be slowed less in the second medium than in the first. But it can only be slowed less because the second medium makes an easier passage for it than the medium it is leaving. Therefore, Descartes would say, since light does indeed approach the perpendicular when passing from air into glass, the glass must be giving it an easier passage than the air.

Fermat said in response that it was impossible for glass, which is around 2,000 times denser than air, to nonetheless give light a more unobstructed passage. He said it was impossible for transparent bodies in general to make an easier transit for light when they become denser; and, in reality, that [239^r] would seem fairly strange.

However, because Descartes's reasoning was based on geometry and on the surest principles of mechanics, it could not be shaken by the apparent impossibility cited by his opponent. For that which geometry finds, physics must explain, if it can, since the geometrical principles of mechanics are immovable. Thus Fermat, who was too good a geometer to deny any of Descartes's principles, simply denied the consequence he drew from them. Then, finding himself unable to reconcile this seemingly contradictory effect in physics and mechanics, he resorted to final causes in order to explain what seemed to him inexplicable.

Seeing that it takes neither the shortest nor the most direct path, Fermat dug in and said that it suits both the wisdom of nature's creator and the simplicity reigning in its operations for light to go from one point to another by the path requiring the least possible time. Hence it followed by a proof taken from geometry that, when light passes obliquely from one medium into another, it goes from one point to another by traveling through the contiguous media in the shortest time it can. The sines of its incidence and refraction are between themselves like the different susceptibilities of these two media to being penetrated. But since the sine of light's refraction in passing from air into glass is smaller than its sine of incidence, Fermat concluded that glass creates for light an easier way of passage.

We sense quite easily how Fermat used this reasoning to poorly defend a good position—for a moral principle, a final cause, cannot outweigh a geometrical principle like composite

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motion. As [239^{v}] Fontenelle put it, "When we've learned what is, we shouldn't be afraid of finding too little order; let us not judge what must be, based on order and designs from our own imagination."

Attraction alone could end this dispute

I think it's easy, after what I've said above, to see how attraction unravels this knotty problem.

Light really does accelerate its vertical motion when passing from air into glass, and without that acceleration, it quite definitely could not approach the perpendicular as Descartes claimed. In truth, its motion accelerates because the glass attracts it and because the glass's attraction works with its vertical motion; it is not because the glass creates an easier passage for it. Thus upon passing from air into glass, or into some other medium denser than air, the vertical motion of light is not slowed less as Descartes believed. In reality, that motion is increased by a force unknown to Fermat and Descartes—one which does not depend on the texture of the glass.

It is through this increase in vertical velocity that the angle of the hypotenuse with the perpendicular line decreases; or, in other words, the ray approaches the perpendicular line while passing from a rarer medium into a denser one. And so, by this principle of attraction, the claims of geometry and physics are in agreement. There is no more contradiction to resolve concerning the path light follows when traveling through transparent bodies.

Something completely different happens to a ball when you throw it obliquely into the water. The ball first moves away from the perpendicular—but it does so because [240^{r}] the surface of the water resists it and because the water's attraction, quite apparent on a ray of light, is not perceptible with an ordinary ball.

But we must continue to follow the path of light in transparent bodies and show how attraction guides it, so to speak, through that entire path.

Section 9

Different contiguous media produce refraction

The combination of the attractive force from the media light is passing through is therefore the cause which accelerates or slows its motion in those different media. This cause acts on the ray less as the incidence of the light grows more oblique, but it also acts for a longer time on an oblique ray because it follows a longer line. Thus these effects amount to the same thing, and a ray's sines of incidence and refraction in any two contiguous media are always in an inverse ratio to the velocity of light in those two media. The proof of this is too well known for me to repeat here, but in my opinion the attraction of bodies on light is perceptible in this constant and calculated effect.

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Section 10

Explanation of refraction by attraction

The more we follow the path of light in transparent bodies, the more the power of attraction unfolds to our view.

The disturbance the ray undergoes when passing from one transparent body into another begins, as I've already said, before it reaches the first surface of the body attracting it. The interruption increases as [240^v] the ray approaches the body. Thus before reaching the body it traces a small curved line Bb; for if FF in figure 1 represents the surface of a glass touching the air, and LL is the boundary of the glass's attraction, ray CD will be more attracted as it gets closer to surface FF. For attraction always increases when distance decreases. And so this ray will face unequal attractions at every point in the space between LL and FF, and as a result it will trace a small curve Bb while traversing that space.

When the ray arrives at b—that is, after it reaches the surface of the glass and begins to penetrate it—it is still unequally attracted for a certain period. So if line GH marks the boundaries of this second region of attraction, the ray will still be unequally attracted while it passes through. The asymmetrical attraction occurs for two reasons. First, the attraction of the air the ray is leaving still acts on it slightly and so partially counteracts the attraction of the glass. Second, the parts of the glass the ray is entering act on it unevenly until it moves farther in, like at point d. But by the time it reaches d, all the particles in the glass are acting on it individually and equally, and the air no longer acts on it at all. It can therefore continue its path through the glass in a right line.

I should note that it's quite difficult to determine a cause for the point at which this action of bodies begins and ends. That appears to depend on the laws observed by the attraction bodies exercise on light—and it doesn't seem possible to ascertain those laws completely. In any case, I don't intend to get involved in that investigation here.

The right line drawn by the ray while passing through the glass is a continuation of the curved path which the imperceptible curve Bbd follows to point d. The curvature becomes greater as the medium the ray enters into has a greater difference [241^r] in density compared to the one it leaves.[21]

Now suppose that instead of going from air into glass, the light passed from water into glass. The curve Bbd would then be less curved—since water is denser than air, it counteracts the glass's attraction on light more strongly. Therefore the refraction from water into glass would only be in a ratio of 9 to 8, instead of 3 to 2 as we see in refraction from air into glass (see figure 1).

In my opinion, this is a marvelous demonstration of attraction's influence in refraction.

[21] **Since the curve the ray follows in the beginning of its refraction is almost unnoticeable, we usually take the line of refraction to be a right line which (1) makes an angle with the line of incidence, and (2) contributes along with that line to the very point of incidence.**

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For by what reason would the refraction produced by the glass be stronger or weaker, according to the previous medium's density, if it weren't because the attraction of that first medium weakened the glass's attraction on light, and was able to do so because of that medium's very own attraction on it?

Now again suppose another case, where instead of passing from a rarer medium into a denser one, light goes from the denser to the rarer medium. Here it's easy to see that the curvature of the imperceptible line I just mentioned will go in a different direction, and its convex side will be toward the perpendicular. For in this case the attraction of the denser body will pull the ray from there upward.

Section 11

On the light which goes through glass a second time at a certain incidence

[241^v] It is still the combination of the attractive forces of the media light goes through that determines at what obliquity of incidence it will be transmitted or reflected.

Suppose light falls on a piece of glass and makes an angle of incidence BDE of more than 42 degrees. Just as it should be leaving the glass, instead of penetrating into the air next to it, the light goes all the way through the glass again. As it does so it makes a perceptible angle equal to that of its incidence upon this same surface AB (see figure 4).

How attraction produces this phenomenon

Only attraction, the universal spring of nature, gives a tangible reason for this phenomenon.

For all incidences, the attracting force of the glass opposes the light's vertical motion as soon as it arrives at its last surface and leaves it to pass into the air. For in such a case, the glass's attraction draws the ray toward it continually. This is why oblique light always moves farther away from the perpendicular when going from glass into air—it does so, as I've already said several times, only because its vertical motion is diminished. Now we know that light has less vertical force as its incidence grows more oblique (since, if it were horizontal, it wouldn't have any [242^r] at all). We also know that the sines of incidence and refraction are always, between themselves, in an inverse proportion to the ray's velocity in the two media the light is traveling through. Given these facts, let's take a case of light passing from glass into air. Suppose the light's vertical velocity is such that, by the impediments to that velocity from the glass's attraction, the sine of refraction in the air becomes the ray of the circle for which it is sine (this happens when the incidence upon the glass rises above 42 degrees). In this situation, the ray will not be able to penetrate farther into the air next to the glass. When it arrives at B, it would follow the line BB[22] tangent to

[22] **The ray at point B, if it stopped being attracted, would in this case be just about of an average**

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point B if in that moment it stopped being attracted. But since it constantly acts on the ray, the attraction of glass CD in figure 5 pulls it from line BB at every moment by attracting it from O toward Q, from I toward H, and so on. Thus the ray, in response to these continual efforts of the glass's attraction, goes through the glass again by tracing a small curve NBK. This curve will be a sort of parabola with vertex at point B (according to Galileo's proof, which in this case we can apply to light). The ray will travel the glass again through certain degrees of velocity in the reverse order from those it experienced after its entrance into the glass at N all the way to point B. For from B to K the glass's attraction will return to the light all the velocity it took away from points N to B. At K on the upper surface of the glass, the ray will then make a perceptible angle equal to its angle of incidence at N.

It is only by the finest and most delicate experiments that we manage to discover this sort of parabola, almost unnoticeable, which the ray follows when passing from the glass into the air with the right obliquity of incidence. It is certain, however, that it does trace this curve, and that attraction [242*v*] is the perceptible cause of it. In this case we can say that the cause is tangible, even though the effect is almost unnoticeable.[23]

This reflection of light at a certain obliquity of incidence is so much the effect of attraction that you could put water on the other side of glass CD instead of air (see figure 5). As long as the incidence stays the same, ray AB will penetrate into the water instead of going back through the glass. So that the ray can go through the glass again when it's next to water, the angle of incidence has to rise beyond 42 degrees. It's easy to see why the obliquity must be greater in order to produce a total reflection when going from glass into water than when going from glass into air. Since water is denser than air, it counteracts the glass's attraction more strongly and for that reason makes the light do two things. First, the water forces the light to penetrate into its substance. Second, it causes it to follow the right line NG with the same obliquity at which the light returned toward the glass at B, at I, at E, and so on, when the glass was next to the air.

When light passes from water into air, its angle of incidence must rise above 49 degrees in order for it to be reflected. Since water has less attractive force than glass, there must be less vertical force so that the water can force the light to go back through its substance instead of breaking out into the air.

The diamond, which is the densest transparent body we know of, produces a total reflection when light's incidence upon it is just 30 degrees. It is on this principle that jewelers cut diamonds, even though they probably don't know the reason for it. [243*r*] Thus all media reflect light, or let it pass at obliquities of incidence which are greater or lesser according to the different densities of the media. (As always, I'm leaving out

reflection. We know that such a reflection occurs when the moving object, after losing all its vertical velocity, would retain only its horizontal velocity.

[23]*mais il est sûr, qu'alors il décrit cette courbe, et que l'attraction en est la cause sensible, et l'on peut dire que dans ce cas, la cause est palpable, quoique l'effet soit presque insensible*

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sulphurous bodies.)[24]

Finally, consider what happens when the density of the medium light is entering approaches that of the medium it is leaving. Here there must be greater and greater obliquity of incidence in order for the light to be reflected so that, when it goes from a rarer medium into a denser one, it is completely transmitted (however oblique its incidence may be, so long as it isn't totally horizontal). For the attraction of the denser body always forces the light to pass into its substance.

Section 12

Until now I've considered transparent bodies only in cases where bodies with parallel surfaces transmit light, without uncovering for us any new property in light.

On the refrangibility of light

But we know that when the surfaces of a transparent body are inclined toward each other, like those on a prism, then light passing through them is tinted various colors within it. We also know that the glass, by affecting different rays, causes the various refractions which separate the rays to appear. These different refractions are imperceptible when the ray travels through a glass with parallel surfaces. This is because, in passing from the glass into the air, the ray clearly moves away from the perpendicular just as much as it had approached it when going from the air into the glass. The second of these refractions

[24]Here the Paris I manuscript contains a new paragraph which is absent in the Basel text. The Paris I paragraph reads, "The comparatively greater refraction which bodies and the diamond produce, given their density, can be deduced quite well from the attraction which bodies exercise on each other at the point of contact. For the shape of the particles makes extreme changes to the energy of this attraction (*la figure des particules change infiniment l'énergie de cette attraction*) by increasing or diminishing the tangent points. This attraction has a perceptible effect only at very small distances, and it increases exceedingly (*infiniment*) in contact, and at that point it is proportional to the quantity of the tangent points. But this subject would lead me too far astray; I shall content myself only with remarking that this attraction of bodies, which is unfolded in contact, decreases at least as the third power of the distances. This is why it is not absorbed by the attraction of the earth; it can have a perceptible effect only between the imperceptible parts of bodies. See Newton's *Principia Mathematica*, book I, propositions 85 and 86." The Paris II manuscript also lacks this paragraph, but Du Châtelet added it herself in the margins. The headings for these propositions in the *Principia* read, respectively, "If the attraction of an attracted body is far stronger when it is contiguous to the attracting body than when the bodies are separated from each other by even a very small distance, then the forces of the particles of the attracting body decrease, as the attracted body recedes, in a more than squared ratio of the distances from the particles" (proposition 85), and "If the forces of the particles composing an attracting body decrease, as an attracted body recedes, in the cubed or more than cubed ratio of the distances from the particles, the attraction will be far stronger in contact than when the attracting body and attracted body are separated from each other by even a very small distance" (proposition 86). See the *Principia*, page 610.

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reunites what the first had separated. But when the glass's surfaces are inclined toward each other, these two refractions occur in the same direction, and the separation between different rays becomes noticeable. The mystery of [243^v] colors then begins to reveal itself.

I won't go into detail here about the experiments Newton did with the prism. We know that these experiments revealed to him what was previously only believed: that a single ray of light is really a beam of seven kinds of different rays, which I've mentioned (chapter 1, section 4); that these rays all break in different proportions when traveling through a transparent body; and that these various "breakings" of different rays are what Newton calls the "refrangibility of light." We now know after him that this refrangibility is the cause of all the colors in nature. Only this property, which Newton noticed in rays, can give the physical explanation of the rainbow, of the colors in the prism, of the changes which occur in colored liqueurs, and so on.

On colored liqueurs

Colored liqueurs must be more heterogeneous and thicker than completely transparent liqueurs, and more homogeneous and less thick than those which are completely opaque. For they are colored only because they stop certain rays in their substance, and transparent only because they transmit others.

Why their color varies with their thickness

The example of red wine's different tinted colors at different thicknesses in a conical glass shows the perceptible reason for the color changes which occur in liqueurs. When you hold them between the light and your eye, the wine at the bottom of these kinds of glasses appears a pale yellow. This is because, since the wine is least thick at that spot, it stops only the violet- and indigo-producing rays. For these rays are, in all circumstances, those which least resist the action of bodies, and the mixture of the remaining transmitted rays should produce a faded yellow.

[244^r] A bit higher where the glass widens, and thus where the wine is thicker, it appears a yellow-orange. At this thickness, in addition to violet rays the wine also blocks blues and greens. In such a case, the mixture of yellow, red, and orange rays—which are the only ones transmitted—produces the wine's yellow-orange color. Finally, at the top of the glass where the wine is thickest, the red rays—the least refrangible—are the only ones transmitted, and so the wine is wholly red. Here the transmitted rays are the same as the reflected ones. The wine appears equally red in both a reflected light and a transmitted light.

If you increased the liqueur's thickness, it would no longer transmit any ray and would then become completely opaque. For the same liqueur can become thicker for only one of two reasons. First, because a greater number of the material particles composing it

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are contiguous (this happens when the vessel containing the liqueur is larger); or second, because some alteration has occurred among these corpuscles. Both these causes produce opacity.

This latter cause sometimes induces a colored liqueur to be formed through the mixture of two transparent ones. It can also make two colored liqueurs become transparent, for since the corpuscles in the liqueurs act on each other, they block or transmit (after their mixture) rays other than the ones they blocked or transmitted before.

On the alterations which the mixture produces in the colors of certain liqueurs

When these corpuscles are divided, the liqueurs [244^v] will allow rays to pass which they used to block. Thus two colored liqueurs will be able to produce one that is completely clear. One the other hand, when these particles join together, the composite can be colored even when the component liqueurs are totally transparent before mixing. For once these liqueurs are mixed, they will block some sort of rays in their substance, unlike when each was separate and they could transmit the rays in equal measure. It is this equal transmission of all the rays that makes liqueurs completely clear.

Now suppose you have two liqueurs, where one transmits only blue rays and the other only red. Suppose they're mixed together. For the same reason as before, they'll become completely opaque—for after being mixed they'll no longer transmit any ray, as the first will block those transmitted by the second.

Why deep water is green

Sea water allows red rays to pass through at a greater depth than it does others rays. This is what Doctor Halley noticed when making his dives,[25] and it's one of the reasons why deep waters appear green. They reflect green and blue rays at the same thickness at which they allow red ones to penetrate.

There are also certain liqueurs, like dye made from *lignum nephriticum*, which allow rays of one color to pass in great abundance while reflecting rays of another color.[26] Such

[25] Halley invented the diving bell, a device that allowed him to remain underwater for extended periods of time. He reported his work with the bell in the *Philosophical Transactions of the Royal Society* for 1716, pages 492–499 (volume 29). Halley's report in the *Transactions* does not mention the optical phenomenon that Du Châtelet describes here, but Newton's *Opticks* (pages 160–161) reported a conversation between Newton and Halley in which Newton learned of the red and green rays underwater. Du Châtelet probably learned of Halley's observations from the *Opticks*.

[26] *Lignum nephriticum*, or "kidney wood," is wood made from either *Eysenhardtia polystachya* (native to Mexico, and the variety Du Châtelet is referring to) or *Pterocarpus indicus* (native to many parts of Asia and the Pacific islands). Robert Boyle discussed *lignum nephriticum* in the context of optics, and Newton mentions the wood in his *Opticks*. For these references and others, see *The Optical Papers of Isaac Newton: Volume I, The*

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liqueurs appear different [245r] colors in reflected light compared to transmitted light. But these details belong to what I have to say about color formation in the fourth chapter of this work.

Optical Lectures, 1670–1672, pages 512–513, especially notes 7 and 10 (edited by Alan Shapiro, Cambridge University Press, 1984).

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Essay on Optics
Chapter 3:
On Opacity, and on Opaque Bodies

Section 1

Definition of the word "opacity"

[246^r][27] Opacity is exactly the opposite of transparence. The word "opaque" just means a body which doesn't transmit light, whether it absorbs the light into its substance or reflects it.

Explanation of this definition

These two effects, however, that opaque bodies have on light—absorbing it and reflecting it—are quite different. Thus it seems that the word "opaque" must be taken as the general term intended for all bodies impermeable to light, but these bodies themselves divide into those that are black and those that are colored.

If there were some body which could interrupt all the light it receives without reflecting any of it, that body would be perfectly black. This is not what happens with darkness nor with reflecting bodies; for darkness doesn't receive any light, and reflecting bodies do send back a portion of the light they receive. A perfectly black body, on the other hand, [246^v] would receive all light without returning any of it.

"But nature allows no precision," as Fontenelle says, and the blackest bodies always reflect some light just as reflecting bodies always interrupt some part of it. But, among all bodies, black ones absorb light most and reflect it least. Thus one could call black, as Milton did, "visible darkness."[28]

[27] Each chapter begins on a recto page; thus the second chapter ends on 245^r, the third begins on 246^r, and 245^v is blank.

[28] *des tenebres visibles*. Book I of Milton's *Paradise Lost* contains the famous lines, "As one great Furnace flam'd, yet from those flames / No light, but rather darkness visible" (lines 62–63). Du Châtelet's gloss of the line as "des tenebres visibles" differs not only from the 1690 Latin translation of *Paradise Lost* (*flammam luce cartentem*) but also from the later 1729 French translation (*les flammes en font une fournaise, mais elles n'y produisent aucune lumiere*). Algarotti also quoted Milton's description in the fourth dialogue on optics from his *Newtonianismo per le dame*, giving it in Italian as *oscurità visibile* (page 159, Naples 1737), which was translated in the French edition as *l'obscurité visible*.

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Section 2

What opacity consists of

Since the homogeneity of bodies is what makes them transparent (see chapter 2, section 4), heterogeneity must necessarily produce opacity. Therefore it's easy to infer that opaque bodies must be more heterogeneous than transparent ones. Thus I shall examine how the heterogeneity of opaque bodies causes them to interrupt and reflect light.

Section 3

The cause of reflection was unknown before Newton

Of all light's effects, reflection is the one we thought we were most familiar with in the past, but in fact it was the one we knew least before Newton. After proving that pore size doesn't produce the transmission of light, he demonstrated that solid parts don't reflect it, and that the more a body's pores are larger and numerous, the more it absorbs and reflects rays.

Light isn't reflected from the top of solid parts

All truths are interconnected, and Newton's discoveries [247^r] are a chain of gold stretching from heaven to earth. The phenomena I've cited to prove that pore size doesn't produce the refraction of light (see chapter 2, section 3) also prove that solid parts are not the ones that reflect it.

Proofs

1. We've seen that obliquity of incidence determines reflection when going from glass to air; but this obliquity doesn't change at all in the crack of a glass. Therefore it isn't the solid parts of the glass which reflect light.
2. Air reflects light at the same obliquity at which water transmits it, but air has fewer solid parts than water; therefore etc.
3. When light passes from a rarer medium into a denser one, whatever its obliquity, it is transmitted almost entirely through that medium. But the denser medium has more solid parts the denser it gets; therefore etc.
4. The reflection of light is a bit stronger in a body you've taken the air from than in air itself. But if solid parts reflected light, more rays would have to come back from a body when its pores are full of air than when they're completely empty; therefore etc.

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5. If the colors produced by a prism in a camera obscura pass through a second prism, the second can be tilted toward the rays escaping from the first in such a way that the red ones, [247*v*] for example, will be transmitted through its substance while the blues, the greens, and others will all be reflected. Now if light were reflected from the top of the glass's solid parts, it seems impossible, at an identical obliquity of incidence, for the blue rays in the prism to only run into the solid parts that reflect them, while the red only encounter pores that transmit them; therefore etc.

6. If solid parts reflected light, then glass, water, and indeed all transparent bodies would be hazy, since they have solid parts, and so the rays which would fall on those parts would be reflected. But because glass, water, and other bodies are perfectly clear, solid parts don't reflect light.

7. If the light rays returning to our eyes from the top of the most polished bodies returned after being reflected on the solid parts making up the first surface of those bodies, they could never be reflected uniformly. Rather, they would be scattered here and there in every direction like beads falling onto rubble. The angle of reflection for the light could never equal its angle of incidence, for a body which appears to us very polished is in truth just a jumble of piles and craters through a good microscope. Mirrors, however, prove to us that the light bearing our image makes its angle of reflection roughly equal to its angle of incidence. Therefore light doesn't come back to our eyes after being reflected on the solid [248*r*] parts of the mirror.

In sum, it's quite certain that rays are not sent back to us by the solid parts of bodies. Hence we must seek another cause for the reflection of light.

Section 4

The differing density between contiguous media produces reflection

While it may be impossible to discover this cause, it will still have been a great service to us to have demonstrated that the solid parts of bodies don't reflect light. To be rid of error is a grand good, even when we'd just have to replace it with enlightened doubt. We must therefore examine nature without losing heart at its obscurities.

We already know that the different densities among contiguous media are necessary for reflection. For we saw in the preceding chapter (section 5) that rays passing without interruption through a piece of crystal—because the crystal's parts are of nearly equal density—are partially reflected when they arrive at its last surface. In this case they find, in the air surrounding the crystal, a medium of a different density which interrupts their transmission and brings about their reflection.

If you submerge the crystal in water, a portion of the rays which reflected when it was surrounded by air now pass into the water, whose density comes closer to that of crystal.

Finally, the more the medium surrounding the reflecting body and that body itself

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differ in density, [248^{v}] the brighter the body's colors will be, and the more abundant its reflection. This is why the colors of fabrics immersed in water or oil are muted, and again it's also why reflected light is more abundant in a vacuum (see the preceding section).

A portion of light returns to us before having reached bodies

This reflection of light, more abundant as contiguous media differ more in density; the equality of its angles of reflection and incidence; the power which bodies have to act on light from a distance, even before it has reached them—all these truths prove to us that a part of the light which returns to us does so before having touched the first surface of bodies, and does so from near that first surface.

Section 5

Newton's conjecture on the cause of this reflection

We haven't yet discovered the quality which causes rays to rebound toward us before reaching the first surface of bodies. After demonstrating this singular truth, Newton had the modesty and good faith to admit that he didn't know its cause. He knew the point where man's mind must stop; and this sobriety of spirit, if I can put it that way, is perhaps as necessary as a genius's understanding to make progress in the knowledge of nature.

Electric matter may be this cause

Newton was therefore content to conjecture that there may be a very fine and very elastic matter, spread out over the surface of all bodies, which serves as a kind of vehicle for light. This matter, perhaps, is just electric matter itself.

One of Hauksbee's experiments on electricity seems to support this idea, that electric matter serves as a vehicle for light to produce the reflection occurring from near the first surface of bodies. In Hauksbee's experiment a glass tube [249^{r}] made electric by rubbing attracted a leaf of copper contained in a glass. If you put a very fine piece of muslin between them then the electric tube would stop perturbing the leaf. The muslin, however, has more and larger pores than the glass. Thus it isn't true that electric matter passes most easily through the most porous bodies.[29]

This agreement between electric matter and light gives us hope that the precision of current investigations into the phenomena of electricity will someday explain the mystery—that is, the reflection of that part of light which returns to us before having reached the first surface of bodies.

[29]See *Institutions de physique*, §61, and the 1742 second edition of *Institutions de physique*, §399, for more on Du Châtelet's view of electricity. See also Q 8, 21, 22, and 31 of Newton's *Opticks*.

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Section 6

The new property of rays noticed by Newton

In light Newton noticed a vibratory motion he calls its "fits of easy transmission and of easy reflection." This discovery casts a faint glimmer into the darkness where the cause of light's reflection from near the first surface of bodies is still buried. He calculated the number and duration of these ray vibrations. He found that they returned at equal intervals, that they were of a durable nature, and that the rays probably had them at the very time they began to issue from luminous bodies.

Application of this new property to the phenomena of reflection

Thus when a ray falling on a body is found in a vibration of easy transmission, and this vibration aligns with that of the matter supposedly spread out over the surface of bodies, then [249*v*] the ray penetrates that body.

If the body penetrated by the ray is sufficiently homogeneous, the ray entering into its substance is transmitted through and the body is transparent.

On the other hand, if the body is heterogeneous, the ray will be extinguished and absorbed, and will lose its vibratory motion in that body, which will then be opaque.

There are other rays whose vibration goes in the opposite direction from those I've just mentioned, and so they're found in a fit of easy reflection. When these rays reach the body's surface, instead of penetrating into it, they reflect from near that surface. Other rays reflect from the midst of the pores. These latter reflections are produced partly by the matter serving as the light's vehicle, and partly by the rays' own vibration, which leads them to be reflected.

We definitely want experiments to confirm Newton's conjectures about this matter "spread over the surface of bodies." We also want them to show how the fits of vibration he noticed in rays contribute, along with the matter, to determining the rays' transmission or reflection.

Nothing would be simpler than to give to some very fine and elastic matter, spread out over the surface of all bodies, control over the reflection of light. For by this hypothesis we would beautifully explain how light can be reflected from within a vacuum, where that matter supposedly always remains. We would also explain by what power light makes its angle of reflection equal [250*r*] to its angle of incidence,[30] how some of the rays can be reflected before reaching the first surface of bodies while other rays penetrate into them, and so on. But the ease with which a hypothesis explains all the phenomena is not a reason

[30] **The equality of the angles of incidence and reflection comes perhaps from the fits of easy transmission and reflection. As I've said, these fits come back at equal intervals.**

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to accept it.[31]

Regarding the fits of easy transmission and reflection Newton observed in rays—his optics speaks of them in such an affirmative way that they seem quite difficult to doubt, given the experiments he established them on. You can see those experiments in book 2, part 4, and in book 3 of this great man's treatise.

I'll speak of these vibrations in greater detail in the fourth part of this work (section 8). In any case, it seems we're forced to admit them in order to explain how, from a certain quantity of rays falling on a crystal, some are transmitted and others reflected. The same goes for a thousand other phenomena which appear inexplicable without vibrations. These phenomena, along with Newton's experiments, help reveal to us these different alternating vibrations of rays.

Section 7

How opaque and transparent bodies differ

It's likely that transparent bodies send back to us [250^v] as many rays as the most opaque bodies do from near their first surface. The quality which makes light rebound before reaching bodies seems to belong both to transparent bodies as well as to opaque ones. This holds whether the phenomenon is due to an unknown cause, or is produced by the action of a very fine matter surrounding the bodies, as Newton conjectured. For this matter, if it exists, is probably the same across opaque and transparent bodies; therefore it must produce a reflection just as abundant over the surface of the former as over that of the latter.

But the light transparent bodies reflect from near their first surface is eclipsed by the infinitely greater quantity they transmit. For this reason the reflection effect is nearly indiscernible on our retina, whereas opaque bodies don't transmit any rays. Those which come back to us from near the first surface of an opaque body produce a very noticeable effect on our eyes.

Moreover, opaque bodies send the rays back to us from within their pores, as I'll say later (chapter 4, section 13); this greatly increases their reflected light.

[31] *Mais la facilité avec laquelle une hypothèse explique tous les phénomènes, n'est pas une raison pour l'admettre.* This idea is common in Du Châtelet's writings—we find it, for example, in her 1738 *Dissertation sur la nature et la propagation du feu*, page 164, where she repeats the idea. See her chapter on hypotheses in the *Institutions de physique*, especially §71; see also §135, as well as §§396 and 397 in the 1742 second edition. Compare Newton's fourth "rule of reasoning" in the *Principia Mathematica* as well.

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Section 8

Since the attraction of transparent bodies on light was proved in the preceding chapter (chapter 2, section 7), opaque bodies must also exercise an attraction on rays. For there is no reason which [251^r] would strip such bodies of the attractive force. Thus this attraction must have an influence in reflection as well as in refraction (chapter 2, section 5).

Attraction doesn't appear to produce reflection from near bodies

Now it's true that attraction doesn't appear to produce the reflection of rays returning to us before they reach the bodies' first surface. But without doubt attraction is not the only spring nature employs; and it would be just as unphilosophical to want to make attraction rule everywhere[32] as it is essential to admit it when the effects demonstrate it. The reflection produced near the first surface of bodies has seemed, up until now, an impenetrable mystery. We know only that the different densities of contiguous media are necessary for it.

Section 9

But it does produce reflection for rays which return from between the pores of bodies

So while attraction doesn't appear to produce the reflection of rays which return to us before they reach the first surface of bodies, it clearly does produce it for the rays reflecting from within the pores of opaque bodies. Opaque bodies send back a number of rays from within their pores, and from between the various surfaces which compose them. These are probably the rays which form their different colors; for if the only rays returning to us were those reflected from near the first surface of opaque bodies, these bodies would all appear the same color. This is true because, if there really is a very fine and elastic matter spread out like a varnish over the surface of bodies, that matter is the same over all bodies. Consequently it doesn't differ among blue and red bodies. And if this matter doesn't exist, there's no [251^v] reason why the light returning to us before it reaches the first surface of all bodies has to be of the same color. Whereas the different arrangement and size of particles making up bodies of different colors act distinctly on differently-refrangible rays, those rays returning to us from between the pores of a green body, for example, are not those which come back from between the pores of a yellow body. This is probably the

[32] *il serait aussi peu philosophique de vouloir la [attraction] faire régner partout*. Compare the 1740 *Institutions de physique*, §389: "The Newtonians who make of attraction a property inseparable from matter, want to make it reign everywhere" (*Les Newtoniens qui font de l'attraction une propriété inseparable de la matiére, la veulent faire régner par tout*).

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cause of colors for opaque bodies, as I'll explain in greater detail when I speak of color formation in the fourth chapter (section 5). For now in this chapter, I still have to show how, in general, attraction produces reflection for rays which return to us from among the pores of opaque bodies.

Since light is transmitted through a body, when the body's particles (being of a nearly equal density) attract the ray equally from all sides, it must change direction upon encountering a body whose particles are of an unequal density. Or—and this has the same effect—the ray may encounter a body where the particles are separated by large pores, full of a matter much rarer than that of those same particles. For in such a case the particles attract the ray unequally, and so does the heterogeneous matter separating them.

Reflection and refraction, two effects of attraction

This unequal attraction exercised by the particles of opaque bodies produces the same effects we've seen induced by hetereogeneous media at different obliquities of incidence. Thus when any particle's attraction is strong enough to counteract the light's vertical force, the ray is reflected; but if the [252^r] attraction is weaker, the ray just gets broken, or refracted. This means that bodies reflect and refract light by the very same power, set to work in different ways—and this power is attraction.[33] We can consider the reflection of light as a greater refraction, since it's really just a greater effect of a common cause. In the same way, we sometimes take the refraction of perceptible bodies to be a reflection from beneath. In what follows we will see more and more how much reflection and refraction are alike.

Section 10

The size of pores produces reflection

Pore size brings about these reflections and refractions, which the rays undergo inside opaque bodies. This is why a body's pores can't be larger than a certain limit for the body to stay transparent. For since the pores of bodies are either empty or full of a matter infinitely finer than that of the particles encircling them, light is unequally attracted to a greater degree as it finds more of these empty spaces to go through, and as these empty spaces become larger.

One might think that more internal refractions are produced in opaque bodies where the pores are narrow, and more reflections in those where the pores are large. This [252^v] would probably be because the particles which force the ray to bend act on it for longer as

[33] **You'll notice I'm speaking here only of the light returning to us from within the pores of opaque bodies, and not of light reflected before reaching the bodies' first surface. As I said above, in section 8, that reflection doesn't seem to depend on attraction.**

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the pore it passes through becomes larger and as this action, continued for longer, thereby forces the ray to reflect and return toward our eyes.

However, when the pores are too large, the rays penetrating too far forward into the body are extinguished by the number of reflections they undergo—just like when a ball loses its motion by bouncing, or when sound weakens through repeated echoes. Thus the bodies whose pores are very large send back to us less light than if their pores were smaller. A certain pore size is necessary in order to produce abundant reflection, just as it is for refraction.

Black bodies produce more refractions than internal reflections

As I've already said, black bodies are those which reflect the least light, and it appears that more refractions than reflections are produced inside such bodies. For since their parts are very fine, the pores separating them must be very small. Therefore the rays arriving at the first surface of these bodies are extinguished and absorbed into their substance by the refractions which both their discontinuity and heterogeneity cause light to undergo. No light returns to us from between the pores of black bodies; that's why their reflected light is so weak that it's always eclipsed by the light sent back to us from their surroundings. This is the reason they appear black.

What makes colors of bodies more or less bright

So in order for a body to be completely opaque, its pores must be very small, very numerous, or very [253r] large, and either totally empty or full of very rare matter. Black bodies probably fall into the first group. In order to reflect bright colors, a body's pores must be large without being too large. If that's the case within the pores, a great abundance of rays will return to us.

At this point, what's left is to examine how different bodies reflect different colors.

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Essay on Optics
Chapter 4:
On the Formation of Colors

Section 1

Refrangibility is the cause of all colors

[254^r][34] All colors in nature stem from this property of light discovered by Newton, which he calls its *refrangibility*.

Opinion of philosophers who didn't acknowledge this refrangibility

Before him, the better philosophers believed that colors were formed by the various modifications which bodies impress on light, or by the unequal mixture of light and shadow. But Newton demonstrated both to the mind and to the eyes, with countless experiments you can see in his treatise on optics, that a ray of solar light—appearing a brilliant white to us, bordering on yellow—actually contains seven kinds of rays. These all break in different ways when passing through any transparent body. Newton also showed that, once they're separated, the rays' color remains fixed over time. Lastly, he proved that each kind of ray is set by its nature at a certain degree of refrangibility, as also at a certain color.

Section 2

Action of bodies on light is necessary to make colors appear

Since all seven kinds of rays issue from the sun at the same time, however, the colors composing light would be hidden from us, and everything would look the same color as sunlight, if bodies didn't act on the rays. Thus the action of bodies [254^v] on light is necessary for it to reveal its colors. But this action is limited by the very nature of the rays, and when bodies act on them, they by no means change anything about that nature. They merely give the rays the chance to uncover it.

[34] Each chapter begins on a recto page; thus the third chapter ends on 253^r, the fourth begins on 254^r, and 253^v is blank.

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Section 3

How light reveals its colors to us, and the definition of refrangibility

Take a prism, for example. Upon receiving a beam of white solar light, the prism attracts it by its mass and, as we saw in the second chapter (section 6), forces it to bend while passing through it. If this light beam contained only a single kind of ray, they would all obey equally the force acting on them; and if the prism didn't act on them, they'd go through it just like they fell onto it. But since this light beam is composed of seven kinds of different rays, and since the prism attracts them by its mass, the seven rays resist the action by which the glass attracts them, doing so more or less, according to their nature. As this differential resistance untangles them from each other, they make distinct and separate impressions on our retina, and colors become perceptible. Therefore refrangibility is, in effect, just the different ways each kind of homogeneous ray resists the action of bodies.

Section 4

Opaque bodies act on light

Transparent bodies only make colors appear by the action they exercise on light, and sunlight appears homogeneous to us when no body acts on it. Given these facts, it's certain that opaque bodies would appear to be of one and the same color as light if they didn't exercise any action on the rays arriving at them. Thus the various colors of opaque bodies prove to us that these bodies act on light.

The most refrangible rays are the most reflectable

[255r] All experiments confirm this origin for colors, and the most refrangible rays (that is, those which divert most from their path when passing through any transparent body) are always the most reflectable—they reflect at a lesser obliquity of incidence. These rays maintain their refrangibility after reflection. Thus after reflecting from the top of any body, homogeneous rays come together again at different foci behind a lens, and these foci correspond to the various degrees of refrangibility. Therefore refrangibility seems to be a property of rays which cannot be stripped from them.

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Section 5

What happens to transparent bodies suggests what happens to opaque bodies

Colored transparent bodies[35] are in between opaque bodies and completely transparent ones, and it's by analogy to them and to opaque bodies that we can discover the cause which makes a body reflect one color rather than another. For only in transparent bodies may we perceive the path of light.

Transparent thin bodies become colored

All transparent bodies become colored when you blow on them in bottles, or when (in whatever way) you stretch them into plates.[36] Consider, for example, rays transmitted without interruption by the homogeneous particles next to a transparent body when that body was thick. [255^v] But when the body is thinner, these rays no longer encounter particles of an equal density, and so they reflect upon meeting the air. The air's density differs from that of the transparent body and interrupts the rays' transmission, thereby producing their reflection.

Section 6

Their color varies with their thickness and with the position of the eye viewing them

Transparent bodies don't just become colored when they're very thin; their colors also vary with their thickness, and according to the obliquity of the light they send back to us. Thus *aqua crispata* seems to be of different colors according to the thickness of the bubbles constituting it, and according to the position of the eye observing it.

[35] **I've already spoken about transparent colored bodies in section 12 of chapter 2. But there I dealt with them mainly in relation to the rays they transmit; here I intend to show the analogy between these bodies and the particles of opaque ones. Thus I'm considering them here more especially in respect to the rays they reflect.**

[36] "Plates" translates the French *lames* here, and throughout the rest of the manuscript. In his *Opticks*, Newton speaks of "plates of glass," "plates of air," and "plates of water" to refer to thin layers of these materials. In translating the *Opticks* into French, Coste rendered "plate" as *lame*. See, for example, the beginning of book II part 1, in both English and French.

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Section 7

What sublime use Newton made of what we call soap bubbles

No part of nature is too small for a philosopher. Newton dared to measure the thicknesses at which a soap bubble, whose subtlety and colors change at every moment, gives off different colors. With the help of these measurements he determined the thickness necessary for any particle to reflect back to us this or that color. Hence these discoveries—so fine that they didn't seem made for human nature—arose before his eyes from the midst of a contemptible amusement. On this occasion one could say to Newton—"from the baubles of babes and sucklings hast thou drawn the truth."[37]

It is by means of these bubbles that he measured the thickness of the particles which reflect different colors

Two glasses from a telescope gave him the means for making these strange measurements, for which the soap-balls had given him the idea. Since the first of these glasses is flat and the second convex, the air or water which slipped between them had various thicknesses. It therefore had to give off different colors at those thicknesses, just like the ball of soap. Now, because the sphere [256^r] on which the convex glass had been cut was known, Newton determined in this way the thickness at which the plate of water between the glasses reflected or transmitted different rays. He then applied his findings to soap bubbles as well, which appear different colors at different thicknesses.

Section 8

Results of these measurements

The results of Newton's measures and experiments on this subject are as follows:

1. Violet rays—which are the most refrangible, and which reflect at the least obliquity of incidence—are also those reflected by thin plates at their least thickness. These films reflect red rays, the least refrangible, at their greatest thickness, and act similarly with other colors. This proves quite clearly what I said above in section 4, that the colors of opaque bodies come from the different thicknesses of their particles.

[37] Du Châtelet pens her quip to Newton in Latin: *ex jocis infantium et lactentium traxisti veritatem*. The remark could be a tongue-in-cheek reference to a passage from the Vulgate, where Psalms 8:3 reads, *ex ore infantium et lactentium perfecisti laudem*, or "out of the mouth of infants and of sucklings thou hast perfected praise" (Douay-Rheims English translation).

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The particles forming red are the largest

2. The particles which reflect red must be, all else equal, the largest of all. The particles for other rays must be less thick in proportion to the refrangibility of the light they reflect.

3. The colors of these plates change according to the obliquity of the eye observing them. This cannot be otherwise, for different rays reflect at different obliquities of incidence, as I said in chapter 3 (section 3). Rays reflected at a certain obliquity therefore differ from those which reflect at some other, and the same film must appear as different colors to different people. This is because the rays which the film sends back to them return at different angles.

The admirable relation between refraction and reflection

[256^{v}] 4. The thicknesses at which a plate of water or air reflects colors are, among themselves, like the sines of light's refraction in two media. The result is that a plate of water reflecting violet, for example, is a quarter less thick than a plate of air reflecting the same color; and the sine of refraction in the water is less than a quarter than the sine of refraction in the air. Consequently the colored rings were smaller in the water and larger in the air. Thus as a body is denser, it needs less thickness to reflect any color, and vice versa.

From this we can conclude that the particles of very dense colored bodies must be smaller than those of bodies with the same color but less density. For instance, the particles of a yellow ribbon must be larger than those of a gold piece.

This admirable connection between reflection and refraction plainly shows that these two effects depend on the same cause, and that this cause is attraction. For attraction acts through mass, and we've just seen that a body requires less thickness to produce some effect on light when that body is denser.

Homogeneous rays are transmitted and reflected in turn according to the thickness of the thin plates

In a camera obscura, if you allow one of the colors escaping from the prism to fall on the two glasses of a telescope (which Newton used to make the discoveries I'm explaining), then the rays of that color will be transmitted and reflected alternatingly by the plate of air or water compressed between the glasses. The result is that each colored ring will be separated by a dark one which doesn't reflect any light. This [257^{r}] dark ring, viewed between the air and the eye, will look like the prismatic color illuminating the glasses.

The proportion of this alternating transmission and reflection

This alternating transmission and reflection occurs at equal intervals, and continues in an arithmetic series with the numbers 1, 2, 3, 4, 5, 6, and so on. And since no reflection

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took place at the point of contact between the two glasses, the rays which were transmitted at thickness 0 continued to be transmitted at thicknesses 2, 4, 6, 8, etc. On the other hand, those reflected at thickness 1 continued to be reflected at thicknesses 3, 5, 7, and so on. The thicknesses changed according to the kinds of rays falling on the glasses.

This phenomenon would be enough to prove that solid parts don't reflect light

It will be useful to note here that the alternating reflections and transmissions of rays through thin sheets, according to their different thicknesses, would be enough by themselves to prove that it's not a body's solid parts which reflect light (see chapter 3, section 3).

Definition of fits of easy transmission and easy reflection

It is this property which rays have, of being alternately transmitted and reflected through thin plates in a constant proportion, that Newton calls their *fits of easy transmission and easy reflection*. I've already spoken about this new property of light in chapter 3, section 6. The "fits" just denote that quality, whatever it is, by which one sort of homogeneous rays—falling on any transparent body at one and the same angle, and being transmitted at thickness 0—continue to be transmitted at thicknesses 2, 4, 6, 8, and so on, and reflected at the intervening thicknesses of 1, 3, 5, 7, and others.

These alternating transmissions and reflections are only perceptible when the transparent body is very thin. For when bodies are of a certain thickness, the rays are [257^{v}] forced to pass through them, by an equal attraction from all their parts, without interruption; and therefore the body looks completely transparent to us (see chapter 2, section 4).

These fits are one of the causes which make very thin transparent bodies become colored. The rays which were in a fit of easy transmission find their transmission interrupted when the thickness of the body decreases. They must then be reflected upon encountering a new medium, which takes the place of the homogeneous particles that used to be reflecting them.

These fits follow the degrees of refrangibility of rays

These fits follow the different refrangibilities of rays, just like reflection does, such that they're larger and less numerous in red rays (which are the least refrangible) and smaller and more frequent in violet rays (which are the most refrangible). This occurs in a proportion of just about $14\frac{1}{3}$ to 9, which is nearly a tenth the inverse proportion of the intensity of the violet and the red in the prismatic image. In that image the violet is to the

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red as 80 is to 45.[38]

Section 9

Thin plates transmit one color and reflect another according to their thickness

When the glasses of the telescopes from this experiment were illuminated by light direct from the sun, there was no darkness except for the central spot formed by contact between the glasses. [258*r*] In that location no perceptible reflection was produced, but the air or water bound between the glasses was tinted different colors at all different thicknesses. Since light from the sun is composed of all kinds of differently-refrangible rays, and since these rays are transmitted or reflected at different thicknesses depending on their refrangibility, some rays reflected at all the different thicknesses of the plate of air between the glasses. This took place with sunlight, whereas the rings were alternately colored or dark when the glasses were illuminated by a single kind of prismatic light.

From this observation it follows that:

1. The air or water compressed between the glasses transmitted one color and reflected another at the same thickness. Also, when looking at these glasses before the day, the rings formed in between seemed to look one color in transmitted light and another in reflected light, such that the same plate which reflected blue rays transmitted the red, one which reflected yellow transmitted violet, and so on.

Colors are brighter when the plate reflecting them is thinner

2. Colors are all the brighter when the plate reflecting them is thinner. For colors are brighter as the rays forming them are more homogeneous, or less mixed with other rays. Thus, as a side note, there are no colors brighter than those of the rainbow, because there are none more pure. Now since differently-refrangible rays are reflected from the top of the thin films at different thicknesses, the thicker a plate is, the more it will reflect different kinds of rays, and so the plate's color will be fainter as well. Therefore bodies with a very bright color [258*v*] must have very thin particles.

Different orders of colors

3. From these points it also results that there are different orders of colors, according to how pure or mixed they are. We call the purest ones—that is, those produced by the

[38] **Since violet rays are in all cases those which bodies act on most, violet must be more expanded in the prism image and more contracted in the colored rings of thin plates. For in the first case the prism separates the rays, while in the second case the thin plate reflects them.**

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thinnest plate—*first-order colors*. We call those produced by a plate three times thicker than the first *second-order colors*. We could go on as the colors are more or less mixed and as the thickness of the plate reflecting them increases. For this thickness increases in the following arithmetic progression: 1, 3, 5, 7, and so on.

Section 10

The reflection of differently-refrangible rays at different thicknesses and obliquities is what causes the colors of thin bodies to vary with the obliquity of the eye observing them. For this reason the color returning to our eyes at any one angle is not the same one which returns at every other angle. This is the true cause of colors in the rainbow, a cause unknown until Newton.

Section 11

What makes the colors in changing bodies

When thin plates are rarer than the medium surrounding them, the obliquity of the rays returning to our eyes makes a greater change in their colors than when the films are denser. Thus the colors of the soap bubble were brighter and less changeable than those of the water or air compressed between the glasses. This is easy to deduce from the laws of refraction. For when light passes from a denser medium into a rarer one, refraction occurs while moving away from the perpendicular; if you switch the mediums, it occurs while approaching it. For example, suppose that Rr (in figures 6 and 7) are two thin plates of an equal density and thickness, with the first being denser [259*r*] than the surrounding medium and the second rarer. The ray will then approach the perpendicular in plate R and will move away from it in plate r. Now line bc, which moves away from the perpendicular, is longer than line Bc, which moves toward it. Therefore the light will come back from particle R at angles which are more different than those it takes in returning from r. As long as the surrounding environment stays the same, the more R's density is increased, the lesser the difference will be between BD and Bc. Thus if the particle's density is so great that the difference in the rays' refraction escapes notice at all obliquities of incidence, the plate will appear to be a single color from every point of view.

This shows that the particles of opaque bodies are much denser than the matter passing through their pores, since their colors are permanent and don't change with the position of the eye observing them.

The plates' colors are brighter when the surrounding medium is rarer than they are, and fainter when the medium is denser. This is because colors are brighter when they're more pure, and it's easy to see that the colors reflected by particle R must be less mixed than those reflected by particle r.

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Causes of the brightness of colors in bodies

Colors are brighter when the medium surrounding the plates differs from them in density. This must be the case, since we've seen that one of the causes of reflection is the differing densities of contiguous media. Now the more abundant reflection [259^v] is, the brighter the colors must be, and so colors are brighter in air compressed between two glasses than in water slipped between them. Air differs from the glass's density more than water does. Thus in order for a body's colors to be brilliant, the particles composing it must be much denser than the medium which separates them.

The medium surrounding the thin plates, therefore, makes their colors more or less bright depending on how much it differs from their density. So the colors of wet fabrics fade but they don't change except upon drying out, and when that happens it's the density of their particles that has been altered. In this way colors depend on the thickness and the density of the particles of bodies, while their brightness depends on the medium surrounding them.

Section 12

Application of the phenomena cited above to the colors of natural bodies

A vague curiosity should never be the goal of our investigations. All the experiments, all the observations I've just related on the colors of thin transparent bodies—these would simply be idle results if they didn't lead us to know, as much as possible, the causes for the colors of different bodies. Therefore I've reported these phenomena, which thin plates of transparent bodies reveal, with such precision only in order to apply them to the colors of natural bodies.

Nature always agrees with herself, said the great Newton,[39] and so there's a strong indication that nature works in the same way in forming the colors of opaque bodies as she does with those of thin transparent bodies. Let us follow, then, as I've already been doing in this chapter, the analogy between the parts constituting opaque colored bodies and the thin plates of transparent bodies.

[39] Du Châtelet gives this quotation in Latin: *natura est sibi semper consona*. She gives the same Latin quotation, without attributing it to Newton, in her 1738 *Dissertation sur la nature et la propagation du feu*, page 130. In the *Opticks*, Newton wrote, "That it should be so is very reasonable, Nature being ever conformable to her self"; that "Nature is very consonant and conformable to her self"; and that "Nature will be very conformable to her self and very simple" (see pages 66, 351, and 372). The idea is similar to Newton's second "rule of reasoning" in the *Principia Mathematica*. William Harvey, the English physician, had used a similar phrase in the preface to his 1651 *Exercitationes de generatione animalium*, writing that "Natura enim divina, & perfecta, in iisdem rebus semper sibi consona est" (page unnumbered, with signature mark "C3").

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Section 13

Opaque thin bodies are transparent

[260^r] 1. The most opaque bodies, reduced to thin plates or dissolved in sufficient solvent,[40] appear transparent when viewed through the aperture in a camera obscura or with a good microscope.

Why this is the case

The fits of easy transmission and reflection of rays cause this transparence in opaque bodies, just as they produced the colors of thin transparent bodies. For bodies are opaque only because they extinguish—that is, they absorb—into their substance the rays which they don't reflect. These rays are stopped in bodies only by the internal reflections and refractions which both the bodies' particles and the rarer medium in their pores cause the rays to undergo. They do this by attracting them unequally based on the various densities of the particles and the medium. Now the rays found in fits of easy transmission, upon arriving at the last surface of a body reduced to thin plates, are transmitted directly into the air. They behave this way instead of refracting like they used to among the different surfaces which made up the body when it was thicker. The air then becomes contiguous to the plate of this body. At that point, the rays still in a fit of easy reflection—instead of being reflected by an unequal action from the body's particles and the intervening medium—find their reflection interrupted by the air and so are transmitted into it. [260^v] Such a plate will be transparent.[41]

Thus when opaque bodies become transparent, what happens among their inner parts becomes, as it were, perceptible to us. Rays which once were undergoing internal refractions, and which were extinguished and absorbed in those refractions, now reach our eyes and produce the transparence of these bodies.

[40] *réduits en lames très minces ou dissous dans des menstrues suffisantes*. In this context, the French "menstrue" means "solvent," or any substance which dissolves another. Under the heading *Menstrue & action menstruelle*, the eighteenth-century *Encyclopédie* explains that *le mot menstrue a été emprunté par les Chimistes du langage alchimique. Il est du nombre de ceux auxquels les philosophes hermétiques ont attaché un sens absolument arbitraire, ou du moins qu'on ne peut rapprocher des significations connues de ce mot que par des allusions bisarres & forcées* ("the word 'menstrue' was borrowed by the chemists from alchemical language. It is one of the things to which the hermetic philosophers attached a completely arbitrary meaning; or at least, one could come close to the known meanings of this word only by bizarre and forced allusions").

[41] **Even if one didn't accept these fits of easy transmission and reflection, what I've explained would be no less true. Whatever the cause leading a ray to be reflected or transmitted, when it finds its transmission or reflection interrupted by the differing density of a narrowed particle, the following effect is no less certain. It must be transmitted instead of reflected, or vice versa, according to the combinations indicated in this section.**

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How opaque and transparent bodies differ

It seems, then, that transparent and opaque bodies differ only in the size of their pores (see chapter 3, section 7). By reducing to very thin plates the arrangement of their parts with the variably dense matter passing through them, transparent bodies go colored and opaque bodies go transparent. They do this without any noticeable change to the density of the particles composing them.

2. Things like mercury, sand, and small animals look transparent through the microscope because it enlarges the spaces separating their particles. Rays which were getting lost among those particles are then transmitted to our eyes. Thus if our eyes were natural microscopes, most bodies would look see-through. But in distinguishing their imperceptible parts we'd become incapable of seeing the whole, and this perspective, far from being useful for us, would actually be quite harmful. God seems to have apportioned all our senses to our needs rather than to our curiosity. As a result we hardly see anything smaller than a flea, and that's because it's the smallest of the animals we had to defend ourselves against. It is therefore quite probable that all particles of bodies are transparent, since those seen through the microscope seem so, and since there are only perfectly solid parts of matter which are opaque.

Why all small bodies appear transparent to us through a microscope

[261^r] This transparence from all bodies is due to the failure of our organs. For if our eyes or microscopes could have us discover the very least part of these particles, that part would certaintly seem opaque to us, since it must be solid. In such a situation, all bodies would look to us like sieves. Newton believes that this transparence of the particles making up bodies is what most obstructs discoveries about their structure.

The colors reflected by opaque bodies are weaker when the bodies are reduced to very thin plates. This is because they return only the rays reflected from among the pores of their first surfaces. But the colors don't change for that reason, because they depend, as I've said, on the particles of these bodies. Here, the particles are not modified.

The transparence of thin opaque bodies proves one of the following things: either the pores in opaque bodies are completely empty, or the matter passing through those pores is finer even than air. The latter would be because the matter reflects the rays transmitted by the air (see chapter 2 section 5).

3. The feathers of certain animals—like the tail of peacocks, the throat of pigeons, and so on—change color as the animals move. These color changes come from the fineness of the nets or whiskers at the end of the feathers. Being very thin, they reflect different rays at their different thicknesses, like the thin plates I've spoken of. Now the rays returning to our eye in one position are not the same as those returning in another position, for the more oblique the rays are, the thicker the reflecting plate is. And as we've seen above

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(section 8), variably-refrangible rays reflect at different thicknesses. This is [261^v] the same reason why spider webs, certain threads of silk, and other bodies change color according to the position of the eye observing them, and upon this principle changeable fabrics are wrought. The whole artifice behind these fabrics consists in forming from them the weft of one color and the chain of another. By this means the rays of one color all return to our eyes at one angle while those of a second color come back at another. This artifice, understood and perfected, has produced changing pictures, those masterpieces of optics. We knew about them before we knew that refrangibility produced them, but only refrangibility can completely explain their device.

4. Several bodies change colors by rubbing their parts together in various ways. Thus some powders used by painters alter their color when crushed, silver turns brown when you rub it, and so on. These are sure signs that bodies' colors depend on the size of the particles constituting them.

5. The colors of the atmosphere visibly change as the particles making them up are more or less condensed. At their least thickness, these particles produce an azure blue, which delights the view and is the mark of absolutely calm weather. Later they form clouds of different colors as they condense and their thickness increases.

Why the majority of wilting plants become red

6. We saw that thin plates reflected red rays at their greatest thickness (section 8). That's also why almost all plants, when they wilt, take a yellow and then a red color in turn. The thickness of the plants' particles increases with the evaporation of their aqueous parts, and [262^r] since the particles are thicker, they reflect the least refrangible rays. These happen to be yellows and reds instead of the greens which they reflected before.

Gold leaf reflects yellow rays and transmits greens and blues

7. Thin opaque bodies transmit one color and reflect another, like the thin plates of transparent bodies that I've talked about (section 8). This proves that bodies extinguish and intercept certain rays in their substances while they reflect others in abundance. The rays they reflect more copiously than others form their color. The thickness of their particles determines which kind of rays they must reflect or absorb in greater numbers, just like we saw before, where the thickness of a thin plate of air or water caught between two glasses determined whether it would reflect certain rays or transmit them. Gold leaf, for example, when seen in a microscope, appears as a green bordering on blue in transmitted light and remains yellow in reflected light. This too proves that gold reflects red, orange, and yellow rays abundantly while absorbing greens, blues, and others into its substance. The same is true for other bodies according to their different colors.

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Section 14

In the interior of opaque bodies, the same thing occurs as in the thin plates of transparent bodies; all bodies reflect all kinds of rays

Since thin opaque bodies produce phenomena so analogous to the thin plates I've mentioned, to me it seems impossible not to conclude that the colors of these bodies depend on the same cause. For I do not see why a flattened body, which is of an equal thickness throughout and so seems to be a uniform color, would not conserve that same color when made into fragments or fibers of the same thickness. Likewise, I don't see why each fiber or fragment would be a different color and why it wouldn't, on the contrary, form [262^v] a mass of the same color as the flattened body. Now since we can consider all opaque bodies to be heaps of such fibers, their color therefore depends on the density and the thickness of the fibers composing them, and on the size of the empty spaces or pores which separate the fibers. The brightness of their colors depends in part on the matter which fills those pores. Thus when I said that opaque bodies were more heterogeneous than transparent ones, that should be understood to refer mainly to the heterogeneity between their constituent particles and the matter which passes through their pores and separates those particles. For it truly does seem like the particles of an opaque body are of an almost equal density, since each body constantly reflects the same color. I affirm that these particles really are of more or less the same density, for there is no body which reflects every kind of ray and consequently none which must contain particles with different densities. Rather, each body takes its color from the prevalence of any one kind of ray in its reflected light. This prevalence comes, as I've said already, from the thickness and the equal density of the larger number of particles which compose it. Thus bodies whose colors are brightest must have, all else equal, particles which are more homogeneous, thinner, and denser than other bodies. This we deduce easily from everything I said in this chapter (sections 8, 11, and 14).

Section 15

Whence each body draws its color

I claim that all bodies reflect all kinds of rays, and this is demonstrated by the same experiment which proves that all colors come from the differently-refrangible rays contained in light. The experiment is done in a camera obscura with the help of a prism, which [263^r] separates the different rays. For if you expose any body whatever to a single kind of these rays, that body will appear to be the color of the ray illuminating it. Therefore all bodies reflect all kinds of rays, since they all reflect any sort of prismatic light you expose them to. But all bodies do *not* reflect all lights in equal abundance. Take ultramarine, for example,

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which when exposed to a beam of blue light will appear more brilliant than cinnabar, while cinnabar would be brighter than ultramarine if you exposed both to red light. It is this overabundance of a certain kind of ray in reflected light that determines a body's color when illuminated directly by sunlight—for that light contains all kinds of rays.

Section 16

All colors appear weaker in light than in daylight. For from the greatest quantity of possible lights, it emits fewer rays than does the sun.

Why green appears blue in candlelight

Certain colors change in candle light. Green, for example, appears blue, because the light from the candle contains fewer yellow-producing rays than sunlight does (sunlight contains more yellow rays than others). This also happens because, mixed into the color green, we find a great quantity of yellow rays; when these diminish, green (which itself is always a mixed color in bodies that reflect it) shades toward blue. For a similar reason everything appears blue in the glimmer from wine spirits, and so on.

Section 17

Experiment proving that sunlight overflows with yellow rays

I've just said that light from the sun contains more yellow-producing rays than others. This overabundance of [263^{v}] yellow rays, perceptible as it is by sight, was demonstrated by Newton with an experiment. He had a piece of gold illuminated by a beam of light escaping from a prism, whose colors had been gathered together by a lenticular glass. The gold appeared completely white by the interception of one part of the yellow rays which made it out of the prism.

We don't know the reason for this overabundance of yellow rays in the light from our sun. Perhaps in other suns other colors dominate; perhaps there are even some composed of colors we have no idea about. For who shall dare limit the power of the being that made them all?

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Section 18

White is an equal collection of all colors; how we have the sensation of white

The particles which make white must be the most dissimilar of all, since white is just a balanced collection of all the rays in reflected light. This is also a truth Newton discovered with admirable shrewdness. You can see the details in his optics. There you'll find that the sensation of white is just a common sensation formed from all the other color sensations. Together these cannot be distinguished from each other, because they act at almost the same time on our retina. Thus based on how fast these different sensations follow each other, there forms a common sensation which we've named "whiteness." This happens in just about the same way as when a glowing coal spun round quickly looks to us like a circle of fire. For our perceptual faculty doesn't extend above or below certain velocities; therefore an extremely slow movement seems to us like true rest.

[264^r] White metals are, of all opaque bodies, the hardest ones to make transparent. This is due to the excessive density of their parts, which makes them reflect almost all the rays falling on their first surface. For we've seen that the more a body's density differs from that of the surrounding environment, the more abundant reflection is.

Section 19

Why white metals become transparent with such difficulty; the particles of black are the smallest of all

I won't recount here the tables Newton gave of the different thicknesses suspected for the particles of different colored bodies. Those which form the white part in metals are, according to him, the smallest of all—if you leave out the particles of black bodies, that is. This is the reason why black is the only color which white metals take on when their parts deteriorate. It's also why fire and putrefaction give bodies a black color, for they break them down merely by dividing their parts.

Section 20

Why black bodies get hot and catch fire so easily

This smallness of the particles of black is what, all else equal, makes black bodies have the least mass in a fixed volume. This too is why they transfer their color so easily to other bodies, for their delicate and discontinuous particles attach themselves freely to the grosser particles of other bodies. Black bodies are also those which heat up and catch

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fire the fastest, as their particles readily give way to the action of fire. Furthermore, black bodies act more than others on light. Since they extinguish and absorb [264^v] almost all of it into their substance, they must be the ones on which fire acts more. The same goes for oily and sulphurous bodies, for the reaction is always equal to the action.

Black is a privation of light

Even though black bodies extinguish the greatest part of the light falling on them, still as I've already said they always reflect some rays. It's possible they send back to us only those rays which return from near their first surface, and that also proves that the color of opaque bodies depends on the rays returning to us from within their pores. For this light which black bodies reflect, when received onto a paper, is not really a color at all, as it were. It seems like a sort of penumbra bordering on dark violet. Thus black is, in effect, just a privation of light. This is why black bodies appear more or less dark depending on whether the surrounding bodies are more or less illuminated.

Section 21

Conclusion

The arrangement of the particles constituting bodies, the form of those particles, the form of the pores separating them, the matter passing between the pores—all these must undoubtedly produce countless changes in even the most circumspect conjectures about the thickness required for particles of different bodies to reflect different colors. But it is no small thing for us to have pushed our investigations so far.

END OF THE *Essay on Optics*

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APPENDIX 1: FIGURES FOR *Essay on Optics*

Seven figures accompany the text of Du Châtelet's *Essay on Optics*, and I have reproduced these figures on the following page. In the manuscript, the figures appear on a single page, 265^r, immediately following the end of the text on 264^v.

The figures have been drawn carefully, with an edge to trace straight lines and a smooth curve in figure 5. These figures therefore contrast with those appearing in the Paris II manuscript, which Du Châtelet appears to have drawn freehand. The figures in the Basel manuscript may have been copied from these earlier drawings of Du Châtelet's.

The use of upper- and lower-case letters together—as in figure 1, which features the symbols "B" and "b"—follows the convention of Du Châtelet's time, and mirrors Newton in particular, whose figures in both the *Opticks* and the *Principia* mix upper- and lower-case letters together.

Figures 2, 3, and 5 from the *Essay on Optics* are virtually identical to figures from Pieter van Musschenbroek's 1734 *Elementa Physicae*. For those figures and other similar ones from Newton, see appendices 3 and 4.

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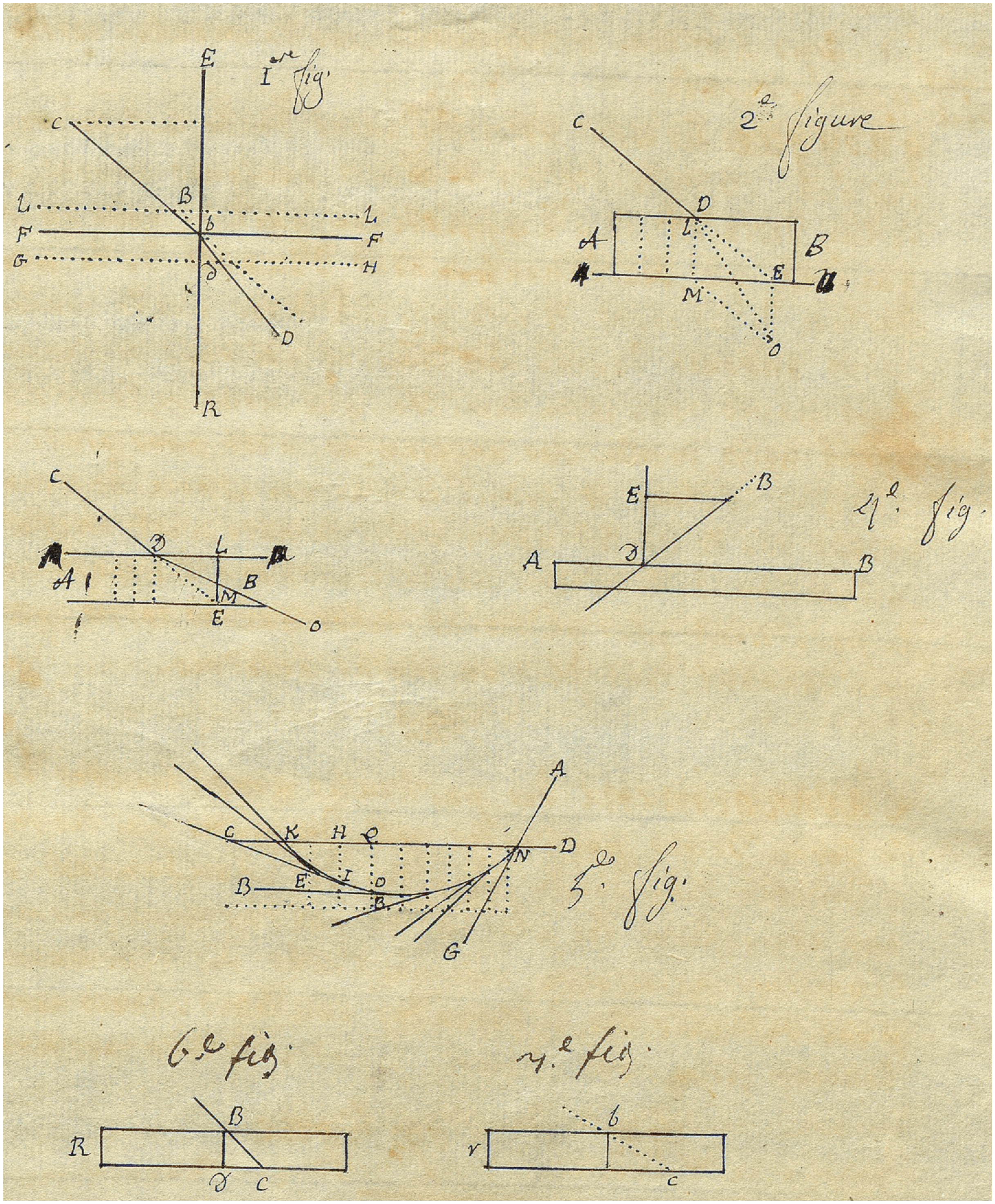

The figures for Du Châtelet's *Essay on Optics*, from manuscript page 265^r.

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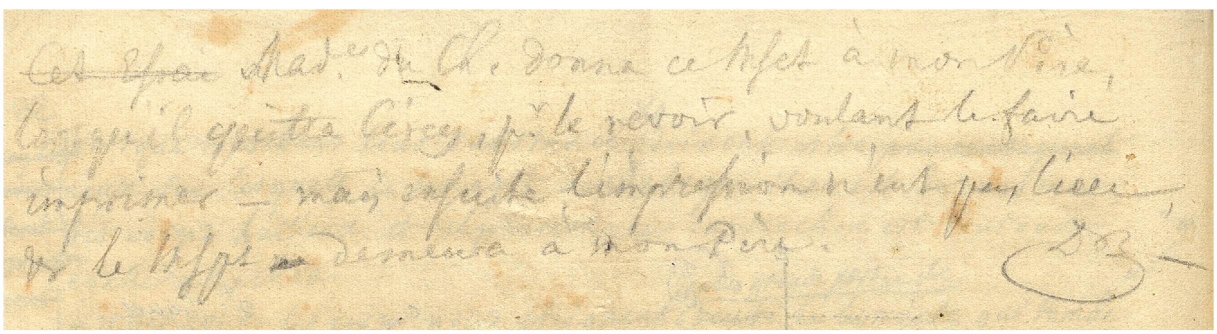
Appendix 2: Daniel II Bernoulli's Note

One of the most interesting questions surrounding Du Châtelet's *Essay on Optics* is why it was never published. It may be that Du Châtelet refused to publish the *Essay* because of fundamental shifts in her views on natural philosophy; see the editor's introduction for more discussion of this point.

Regardless of her reasons, however, a cryptic note left on the manuscript by Daniel II Bernoulli (1751–1834) deepens the mystery. On 265^{v}, the final page of the final leaf, Bernoulli scrawled the message in the image below:



A note by Daniel II Bernoulli, from manuscript page 265^{v}.

The note reads:

> ~~Cet Essai~~ Mad.^{e} du Ch. donna ce Msct à mon Père, lorsqu'il quitta Cirey, p.^{r} le revoir, voulant le faire imprimer—mais ensuite l'impression n'eut pas lieu, & le Mspt demeura à mon Père. DB

In English, "~~This Essay~~ Madame Du Châtelet gave this manuscript to my father to review when he left Cirey, wishing to have it printed. But later the printing didn't take place, and the manuscript remained with my father. D[aniel] B[ernoulli]."

Daniel II Bernoulli's father was Johann II Bernoulli, who visited Du Châtelet at Cirey in March 1739. For more information on this visit, see the editor's introduction.

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APPENDIX 3: FIGURES FROM MUSSCHENBROEK'S *Elementa Physicae* (1734)

Du Châtelet drew from many sources in composing the *Essay on Optics*. The most important of these was Newton's *Opticks*, but work by the Dutch scientist Pieter van Musschenbroek (1692–1761) was influential as well. In a February 1739 letter, Du Châtelet told the bookseller Prault that "I have...Musschenbroek's physics." She does not specify which book in particular she has, however, and so could be referring to the 1726 *Epitome elementorum physico-mathematicorum*, the 1729 *Physicae experimentales et geometricae...dissertationes*, or the 1734 *Elementa physicae*.

The figures from the *Essay on Optics* suggest she possessed the *Elementa physicae*, or perhaps its 1739 two-volume French translation, *Essai de physique*. Like Du Châtelet's text, Musschenbroek's discussion of optics in the *Elementa* relies in a series of figures. Du Châtelet appears to have copied several of these figures for use in her *Essay*.

I have reproduced these figures on the following pages to make the comparison easier. Figures 2, 3, and 5 of Du Châtelet's *Essay* are virtually identical to figures 3, 4, and 7 of Musschenbroek's *Elementa* (marked in red on the next page). These figures appear in "Tabula XI" of the *Elementa*, which accompanies chapters 27–29 (pages 271–294).

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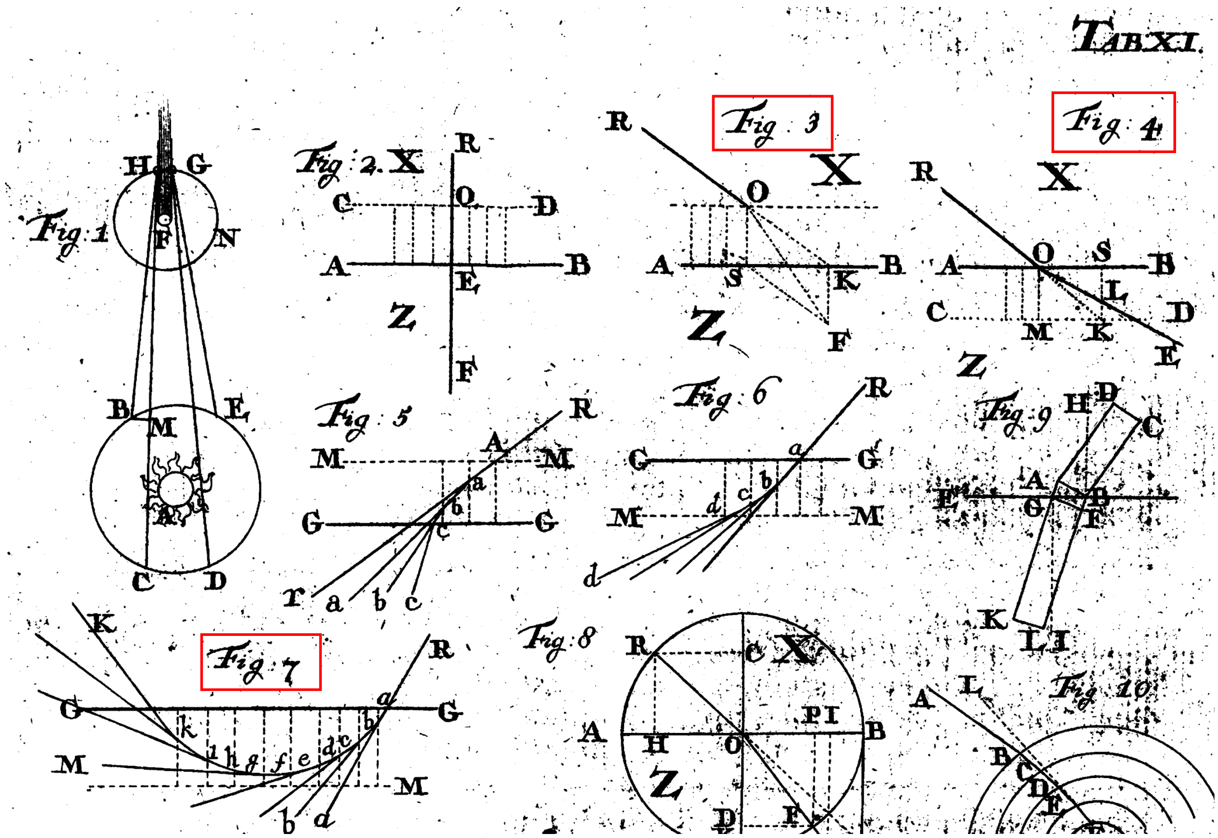

Figures from Musschenbroek's 1734 *Elementa physicae*, tabula XI. Figures 2, 3, and 5 of Du Châtelet's *Essay* are almost identical to Musschenbroek's figures 3, 4, and 7, highlighted above. See the side-by-side comparisons on the next page.

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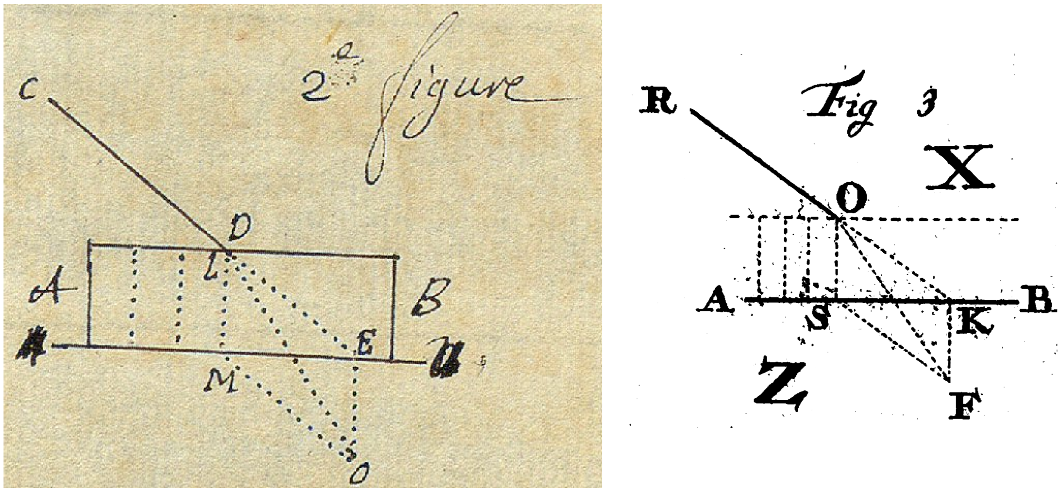
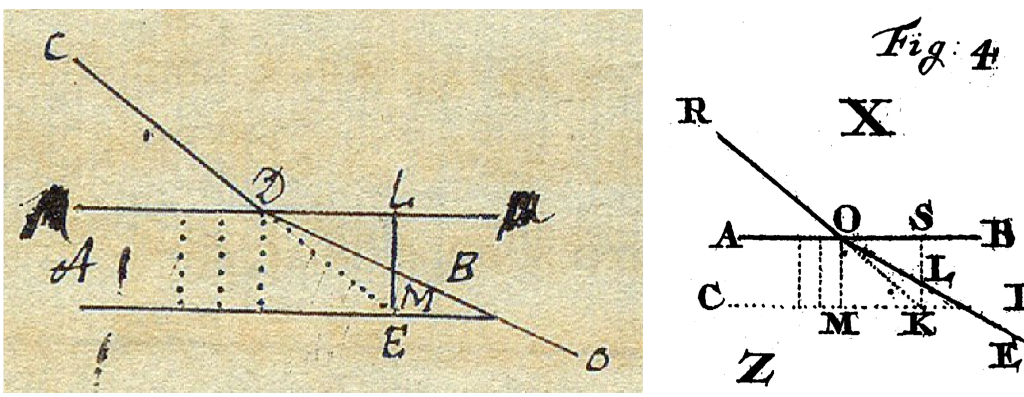
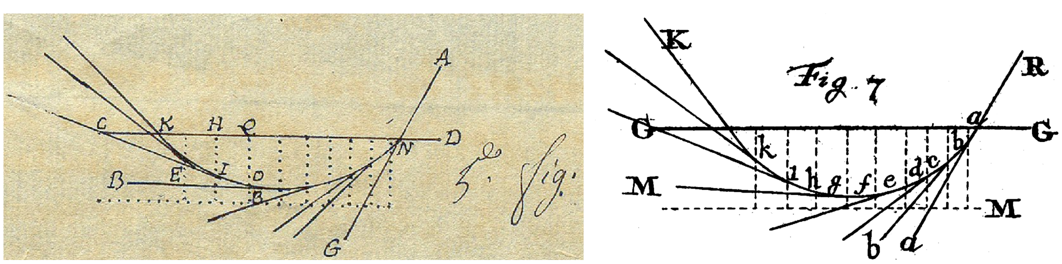


Side-by-side comparison of Du Châtelet's figure 2 and Musschenbroek's figure 3.



Side-by-side comparison of Du Châtelet's figure 3 and Musschenbroek's figure 4.



Side-by-side comparison of Du Châtelet's figure 5 and Musschenbroek's figure 7.

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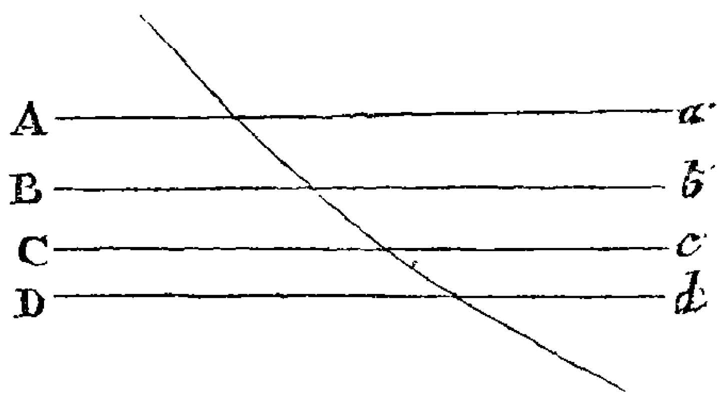
APPENDIX 4: FIGURES FROM NEWTON'S *Principia Mathematica* (1726)

Newton's *Principia Mathematica* doesn't say much about optics, but at the end of the first book, Newton includes a few propositions and figures discussing the behavior of light.

For the sake of further comparison, the figures accompanying propositions 94, 95, and 96 are reproduced here and on the following page. Figure 1 from the *Essay on Optics* is similar to the figures for propositions 94 and 95; figure 5 is similar to the figure for proposition 96.



The figure accompanying proposition 94 in Newton's *Principia Mathematica*.

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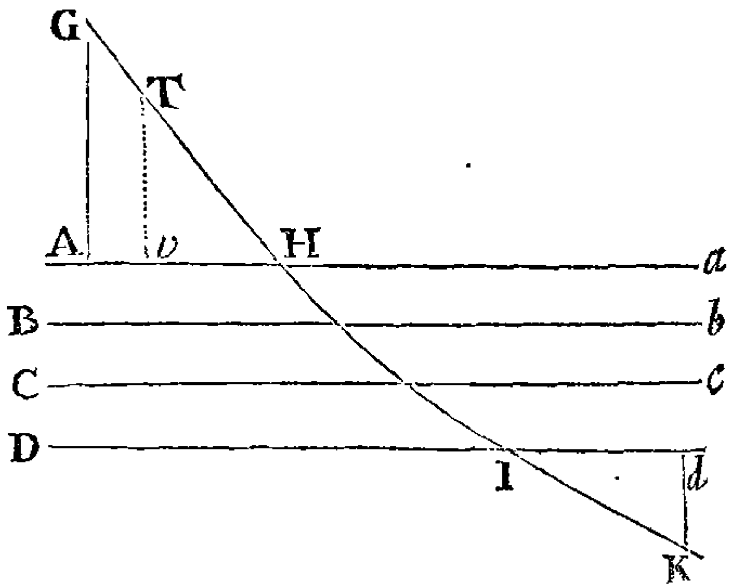
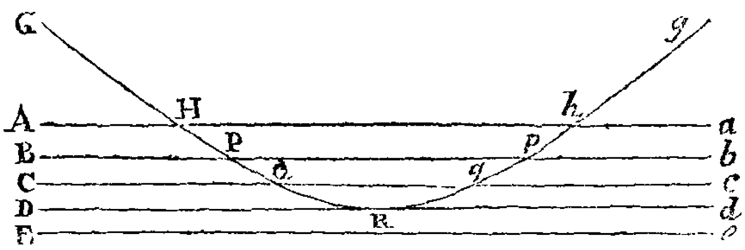


The figure accompanying proposition 95 in Newton's *Principia Mathematica*.



The figure accompanying proposition 96 in Newton's *Principia Mathematica*.

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