Lecture 1
Newton's Initial Investigations on Light and Color

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Contents

This lecture covers the contents of Newton (1672a).

1 Course Admin

1. emails
2. How much math and physics background do people have? I'm considering changing the syllabus to skip the section on classical and relativistic spacetimes, and spend more time on methodology, epistemology, and metaphysics.

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2 Setting the Stage

Historical Background: Knowledge of Light at the Time

1. wave versus corpuscular (particle) theories: everyone held one or the other; none of them agreed on details (*e.g.*, for a corpuscularian, on the relation between the physical properties of the particles and the phenomenal behavior of light and color, whether it was differences in particle mass, size, shape, state of motion, or something else entirely, that caused light to come in different colors)

2. everyone agreed that, in some sense, white light (canonically, sun light) is the "natural state" of light, and that different colors are produced by disturbances of some kind to white light

3. known phenomena: reflection; refraction; transmission through transparent media; propagates in straight lines (appropriately construed); colors change on transmission through and reflection off of colored media and bodies; can cause bodies to increase in temperature (anachronistically put); Law of Reflection; Snell's Law; whole bunch of peculiar, individual experimental results with no understanding of how they may relate to each other in any systematic way, as regimented by an overarching theory (as Newton gestures at throughout Newton (1672a), and in his exchanges with Hooke, Huygens and Pardies)

4. ⇒ no systematic theory (or even loose collection of hypotheses) that could treat and explain even a small number of all known phenomena

Newton's Background: Telescopes

Newton was interested in improving the resolving power of telescopes. That is why he began investigating the refractive properties of glass in the first place, to determine how to minimize the sort of refraction that would impede the production of a clear, sharply delineated image of an object viewed through a telescope. There is a point of deeper than mere historical interest here: for Newton, theory, experimentation and instrumentation were inextricably related. The latter are essential both for constraining the reach of theoretical certainty and for informing the proper way to understand the content of theoretical doctrine (in both metaphysical and semantical senses).

The Instigating Observation

A direct application of the form of Snell's Law as known at the time implied that a circular pencil of light incident on a prism should result in a circular pencil of light leaving the prism. This is not what Newton observed: he observed that the exiting light had the shape of an elongated capsule, a rectangle with semi-circular caps on opposing ends. This is what he attempted to determine the cause of. Remarkably, *no one before him* (of whom we have clear and certain record) had noticed the discrepancy.[1]

[1] The qualification "clear and certain" is required because of the fact that there is slight evidence that Thomas Harriot may have noted the discrepancy in the very early 17th Century. We cannot be sure, because Harriot never published any of his optical work, and his journals and diaries are compressed and difficult to interpret. See the discussion in Stein (unpublished, footnote 21, p. 10–12).

3 The Build-Up to the *Experimentum Crucis*

From Newton's lovingly detailed description of his initial preparations and observations, and from the continuing description of how he settles down to work to isolate the cause of the aberrant phenomenon, we see a man delighted by the physical world, transported into fits of ecstasy by the opportunity to interact with and come to understand it, but all so as to lead him to attend more closely, finely and deeply to it, his experiment not divorced from intellectual cognition and theoretical construction and elaboration but rather inextricably entrained with it.

The Initial Set Up

- his room entirely darkened, all light blocked
- except for a small, circular hole left in the covering of a window facing the sun, so a beam of sunlight enters perpendicular to the window
- a triangular prism placed close behind the hole to intercept the entire beam
- the beam exiting the prism, incident on the opposing wall
- after an intial period of delight in observing the play of colors, he begins to observe "more circumspectly" and is surprised to see the aberrant shape of the beam's image on the wall
- he gives a precise description of the aberrancy:
  1. the image of the light is a rectangle with semi-circular caps on opposing ends, the longer sides in the vertical direction
  2. the straight edges of the rectangle are clearly delineated, the semi-circular caps less so, and he is less certain in his description of them
  3. the length is approximately 5 times the width

Qualitative Attempts to Isolate the Cause

He begins to attempt to isolate the cause by manipulating the experimental situation in ways describable by purely qualitative ideas:

1. different sizes of glass or disposition of ambient light and shadow?
   - passing the light through different thicknesses of glass
   - through holes in the window of different sizes
   - by placing the prism outside the window, fully immersed in sunlight, refraction occuring before passing through hole
2. inhomogeneities in the prism's glass?
   - placed 2nd prism, same shape and glass, against first: light was transformed into size, shape, color
   - the effect of any irregularities, however, should have been magnified, not removed

None had any effect on the aberrancy.

Quantitative Attempts to Isolate the Cause in Kinematics He continues the attempt by the application of more exact methods based on quantitative measurements: he measures angles and lengths and relative configurations of all the relevant objects and images to great precision, to see whether more refined calculations based on the received laws of refraction can account for the abberrancy. That doesn't work.

Attempts to Isolate the Cause in Dynamics He determines that the cause of the aberrancy cannot be in any dynamical complication (*e.g.*, that the light's passage through the prism causes it to propagate curvilinearly rather than rectilinearly).

The Methodology Note the methodology: look for the simplest possible explanations first, test them, dismiss them, both because they are easy to do and because the doing will itself suggest more complex and deeper possible explanations and tests for those in turn.

4 The *Experimentum Crucis*

The term has its origins in the *Novum Organum* of Francis Bacon, where he uses '*instantia crucis*' to mean a determining circumstance that would show that one hypothesis or theory holds true while all rivals do not. I am told (but cannot find the reference) that the term '*experimentum crucis*' was then coined by Robert Hooke, to mean the deliberate construction of a controlled situation whose observed result would provide an *instantia crucis*.

Most philosophers, and perhaps many physicists, today would dismiss the possibility of a single experiment's decisively demonstrating the goodness of a theory (or theoretical account more generally), because of the Duhem Thesis: no experiment ever conclusively tests a single hypothesis or proposition in isolation, because to draw a conclusion from the hypothesis or proposition to test, one must conjoin it with "auxiliary hypotheses" (*e.g.*, principles to interpret the operational description of the experimental outcome so to bring it into substantive semantic contact with the theoretical terms used to articulate the hypothesis, claims about the appropriate isolation of the experimental arrangement from possibly confounding environmental factors, *etc.*), and so the experiment tests only the conjunction of the hypothesis and the auxiliaries *en bloc*.[2] That is as may be, but, as philosophers never seem to realize, and as Duhem himself went on to point out after laying down the Duhem Thesis, while no *single* experiment can ever do the trick, a well designed *sequence* of experiments can, by isolating in turn the possible consequences of each of the auxiliaries and alternatives, so as to dismiss their potential explanatory relevance. And that is exactly what Newton did. The *experimentum crucis* is the culmination of just such a sequence, and that is why, in my opinion, it does decisively and indubitably show exactly what Newton claims it does.

The arrangement of Newton's *experimentum crucis* is shown in this diagram, drawn by him for Newton (1672b), his reply to the second letter by Ignatius Pardies (1672) criticizing Newton (1672a).

[2]This is often called the Duhem-Quine Thesis, or even just the Quine Thesis, but I deprecate those names, because Quine got it so badly wrong. But that's another story.

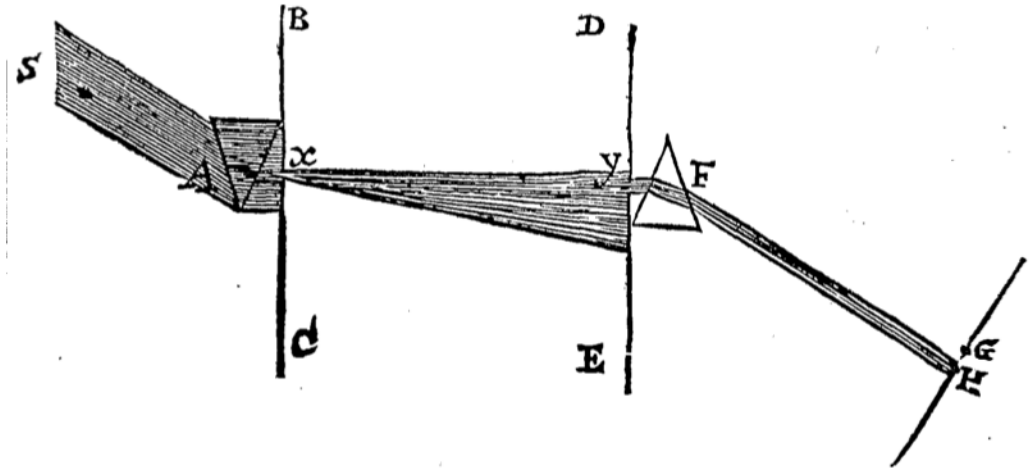

Figure 4.1: *Experimentum Crucis*

The labels in figure 4.1 denote as follows:

S the small, circular hole in the window cover allowing in only a narrow pencil of sunlight (or, perhaps, the pencil itself)

A the first prism through which the entering sunlight passes

B-C the wooden plank behind the first prism, perpendicular to the light's path, blocking almost all the light leaving the prism

X the small, circular hole in the wooden plank **B-C** allowing only a narrow, isolated ray of light leaving the prism to proceed

D-E the wooden plank in front of the second prism, perpendicular to the light's path, blocking almost all the light emanating from **X**

Y the small, circular hole in the wooden plank **D-E** allowing only a further narrowed, even more isolated ray of light to proceed through the plank to enter the second prism

F the second prism, through which the light passing through **Y** travels

G-H the small, circular image of the final ray of light leaving the second prism **F**, where it hits a smooth surface perpendicular to the direction of the ray's path

5 The Doctrine

In my opinion, this is the single most beautiful and amazing venture of experimentation and theorizing working in harmonious concert in the history of science, and one of the most astonishing intellectual achievements in human history.

Note the extreme care and precision with which Newton has, up to this point, described his observations, experimentation, and the results he draws from it: until he announces the principles of his doctrine, *he has never once mentioned anything about particular colors and how they behave*, only properties of light that are objectively quantifiable. It is only with the announcement of his doctrine that he relates the objective properties to the properties describable (at least then) only by subjective, perceptual concepts, *viz.*, the colorific ones.

Newton demonstrated unequivocally:

1. that sunlight consists of an innumerable number of simple light rays differing from each other in their refrangibility relative to a given medium of propagation;

2. that the refrangibility associated with a particular simple ray for a given medium of propagation is a primitive property of that ray in the sense that no manipulation of the ray Newton could contrive would change it;

3. an aside about "metaphysics": it was this fixity of the refrangibility that led Newton to think of these rays as the 'simple' components of the more 'complicated' ray of sunlight, and his denomination of the properties of refrangiibility and colorificity of a ray "of a particular sort" as "original and connate" properties of those rays—though strictly speaking he explicitly denominates only colorificity so, but the intended extension to refrangiibility is, I think, clear, as mandated by his Third Rule of Reasoning in Natural Philosophy (Newton 1934, Bk. III, p. 398–399);

4. that when a simple ray exhibits a particular refrangibility, it also always exhibits a particular correlated colorific character, *viz.*, the appearance to a normal observer under normal conditions of a particular color when the simple ray falls on a white surface, always the same color for a given refrangibility;

5. that light from all sources he could find to experiment on has the property of being composed of simple rays of fixed refrangibility, if it is not itself in the first place such a simple ray;

6. that simple, homogeneal rays manifest a quasi-additive structure in their colorific properties: the composition of two rays close in color (as determined by relative position in the spectrum) tends to produce a complex ray whose color is intermediate between the two

In modern terminology, Newton discovered that:

1. an adequate mathematical representation of any light ray, relative to the experimental technique available to him, has (crudely speaking) a unique Fourier decomposition;

2. the refrangibility of individual components of the Fourier composition—a ray of light of a single pure frequency—depends on the frequency of the light;

3. (visible) light of a single frequency tends to produce only one color, always the same, to a normal observer under normal conditions;

4. and the frequency of a pure, single frequency light ray cannot be changed (at least, again, not by any experimental methods or any physical processes known at the time to Newton);

5. the three-dimensional Maxwell-Helmholtz-Young color manifold has a locally additive structure.

Every single part of Newton's doctrine is still thought today to be true to an extraordinarily high degree of approximation in our deepest theory of light, quantum electrodynamics.

As astonishing as these results were in themselves, and as difficult as they were for many of his contemporaries to digest and accept, in the end it was not the results themselves but rather his method of arriving at and of stating them that caused the most confusion. In his reply to a letter from the French Jesuit Ignatius Pardies, in which Pardies criticized his doctrine of light, Newton makes his clearest statement describing the essence of this method, which suggests some clues as to why Newton's contemporaries may have greeted his doctrine with uncharacteristic confusion; in the process, he also makes a trenchant, penetrating criticism of the hypothetico-deductive method of scientific investigation championed almost universally and almost universally implicitly by his contemporaries, with the exception of Huygens and Hooke who both articulated it method of reasoning or less clearly.[3] This is Newton's statement (Newton 1672b, p. 106):

> . . . [T]he doctrine which I explained concerning refraction and colours, consists only in certain properties of light, without regarding any hypotheses, by which these properties might be explained. For the best and safest method of philosophizing seems to be, first to inquire diligently into the properties of things, and establishing those properties by experiments and then to proceed more slowly to hypotheses for the explanation of them. For hypotheses should be subservient only in explaining the properties of things, but not assumed in determining them; unless so far as they may furnish experiments. For if the possibility of hypotheses is to be the test of the truth and reality of things, I see not how certainty can be obtained in any science; since numerous hypotheses may be devised, which shall seem to overcome new difficulties.

The manner in which Newton deduced and stated his conclusions about the nature of light was completely independent of hypotheses in the sense that they did not depend on any particular hypothesis one may have had about the physical structure of light rays—whether one postulated that they were waves in some ætherial medium or that they were particles or whether one postulated nothing about their physical microstructure at all, Newton's propositions not only made sense but held true. Newton derived his propositions about the behavior of light based solely on his experimental results, with no thought during that derivation of trying to explain the observed behavior by this or that hypothesis; that maneuver, if performed at all, would be only after the fundamentals of the behavior of light were captured by a series of propositions independent of any particular hypothesis about the microstructure of light. To a scientist schooled in the method of science articulated by Huygens, such a feat was incomprehensible.

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[3] For an admirably clear and penetrating exposition of the hypothetico-deductive method, see the introduction to Huygens (1690).

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