Chapter 1

Introduction

1.1 The Conception of the *Opticks*

Newton's plan for a book very much like the *Opticks* gradually emerged in the winter of 1675–6 out of his response to the criticism directed against his first published paper, his "New theory about light and colors" in February 1672. By 1672 Newton was quite accomplished in optics. He began his study of color in 1664–5 while still an undergraduate, and the following year he found that sunlight is not simple and homogeneous but is compounded of rays that differ in color and degree of refrangibility. Based on his investigation of color and his work in geometrical optics, Newton designed and constructed the first reflecting telescope in 1668. When he was appointed Lucasian Professor of Mathematics at the University of Cambridge in 1669, he delivered his first series of lectures on his theory of color, which he then intended to publish.[1] In December 1671 his second reflector was presented to the Royal Society. Its enthusiastic reception prompted him to send a brief account of his "New theory" to the Society for publication in the *Philosophical Transactions*. The paper encountered criticism from Ignace Gaston Pardies, Christiaan Huygens, Francis Line, John Gascoines, Antony Lucas, and above all from Robert Hooke, whose referee's report for the Royal Society incensed Newton. On 21 May 1672 Newton decided not to send a promised paper on the colors of thin plates to the Royal Society, and four days later he wrote to John Collins that he would not publish his *Optical Lectures*: "finding already by that little use I have made of the Presse, that I shall not enjoy my former serene liberty till I have done with it."[2] Newton's sensitivity to criticism and reluctance to publish played a central role in his career.[3]

In 1664–5, when he first encountered contemporary mathematics and natural philosophy, Newton carefully read and learned much from the chapters on light in Hooke's *Micrographia* (1665), especially about the colors of thin plates (an interference phenomenon in modern optics). Yet Newton's notes make it quite clear that he often differed with Hooke. In early 1672 he spent over four months composing draft after draft to counter Hooke's sharp—at points dismissive—criticism of his paper. Newton had also composed his own discourse on the colors of thin plates that moved well beyond Hooke's work. He intended to include it with his reply to Hooke, but he wrote to Henry Oldenburg, Secretary of the Society, that he had decided to send only his reply to Hooke's criticism. He then described the contents of this discourse:

(1) For Newton's *Optical Lectures* and his early optical work see *Optical Papers*, Vol. I.
(2) Newton to John Collins, 25 May 1672, *Correspondence*, 1:161
(3) Westfall, *Never at Rest*, ch. 7, "Publication and crisis."

> The subject of this discourse is the Phaenomena of Plated Bodies, concerning w^{ch} I shall by experiments first show how according to their severall thicknesses they reflect or transmit the rays indued wth severall colours, & then consider the relation w^{ch} these thin transparent Plates have to y^{e} parts of other naturall Bodies, in order to a fuller understanding of the causes of their colours also. And this I purpose to send because it most properly apperteines to y^{e} former discourse of light. . .[4]

This would become the basis for Book II of the *Opticks*.

When Newton first encountered the periodic colors of thin plates in the *Micrographia*, the difficulty of understanding their complex appearance quickly captured his imagination. In his *Micrographia* Hooke had recognized, as no one had before him, that the colors of thin plates represented a fundamentally different physical phenomenon from dispersion and therefore required a different physical explanation from colors produced by refraction. Newton accepted this insight and built his investigation of the periodic colors of thin films on the solid foundation laid down by Hooke. Indeed, his initial investigation of them seems to have been carried out while he was reading and taking notes on the *Micrographia.* Newton's breakthrough came with his development of an experimental method to measure the thickness of the film producing colors. Hooke had been unable to determine these thicknesses because, as he explained, the plates are "so exceeding thin" and his microscope "so imperfect," but he declared determining these thicknesses to be a matter of "greatest concern."[5]

Newton first described his technique in the midst of the second essay "Of Colours" (1666), in which he was recording the experiments that formed the basis for his new theory of light and color.[6] He carried out preliminary experiments and rough calculations that were sufficient to convince himself that his explanation was valid, and he then set it aside to pursue his theory of color. He determined the thicknesses of the plate where a particular color appeared by a technique that has since become known as "Newton's rings." By placing a lens *ABC* (Fig. 1.1), which is just a segment of a sphere, on the flat surface *FBG* of a plano-convex lens he had only to determine the radius of the lens and the diameters of the colored rings produced by the film of air between the plate and the lens. By applying a well-known formula for the sagitta of an arc from Euclid's *Elements*, III, 36, he could immediately calculate the thickness of the air film. If the lens is illuminated and viewed from above, a set of concentric colored circles produced by the thin film of air *ABCGBF* will be seen through the upper surface of the lens. The circles will form an alternating sequence of dark and bright colored rings, and their common center, the point of contact *B*, will be surrounded by a dark spot. Let the diameter of any of these colored circles be denoted by D, the thickness of the air film producing that circle by d, and the radius of the lens by R. Then by the sagittal relation from Euclid $d = D^2/8R$. To establish that the circles do appear at integral multiples of some definite thickness, Newton simply had to measure the diameter

(4) 21 May 1672, *Correspondence*, 1:160. Newton had informed Oldenburg of his intention to send the discourse on 19 March 1671/2, ibid., 122. Newton's notes on Hooke, "Out of Mr Hooks Micrographia," CUL Add. MS 3958, ff. 1–4, are in *USP*, pp. 400–13.

(5) Hooke, *Micrographia*, p. 67.

(6) "Of Colours" is published in McGuire and Tamny, *Certain Philosophical Questions*, pp. 466–89.

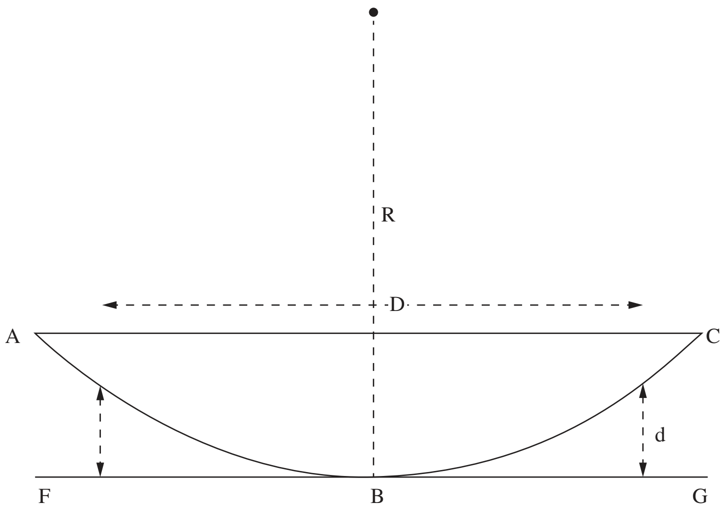

Fig. 1.1 Newton's method of determining the thickness *d* of the air film between the spherical surface of lens *ACB* and the plane surface *FBG* in the production of Newton's rings. *R* is the radius of the lens and *D* the diameter of the rings at the thickness *d*.

of successive circles and see if their squares increased as the integers. To express his result as a modern formula, he found that

$$d = \frac{D^2}{8R} = \frac{mI}{2} \tag{1.1}$$

The intervals I would become the length of the fits in the *Opticks*.[7] Newton returned to the colors of thin plates around 1671—in between the two versions of the *Optical Lectures*—when he carried out an extensive series of experiments and precise measurements and recorded in his essay "Of y^e coloured circles twixt two contiguous glasses." [8] This was the immediate prelude to the "Discourse of Observations" or "Observations" that he intended to send to Oldenburg with his reply to Hooke.

By the end of 1675, Newton had recovered his composure and once again decided to submit his "Observations" on the colors of thin plates to the Royal Society. The 1672 version served as the draft of the "Observations" that Newton sent to the Royal Society on 7 December 1675, together with his new, speculative piece, "An Hypothesis explaining the properties of Light discoursed of in my several Papers," that set forth a physical model of light and its interactions with matter.[9] The two versions of the "Observations" have an identical

(7) For the relation of the intervals *I* to the wavelength in the modern wave theory, see *MSO*, Bk. II, Pt. I, note 19.

(8) Folios 519–28, published by Westfall, "Isaac Newton's coloured circles." For its dating see *FPP*, p. 59, n. 29.

(9) The "Hypothesis" (ff. 538–47) was read at the Society's meetings of 9 and 16 December 1675 and is published in *Correspondence*, 1:362–86. The "Discourse of Observations" (ff. 501–17, *DO2*) was read on 20 January and 3 and 10 February 1676; Birch, *History of the Royal Society*, 3:272–8, 280–95, 296–305, publishes the Royal Society copy, which is reprinted in Newton, *Isaac Newton's*

structure for the first three parts: The first part consists of observations, many of which are quantitative; the second presents a phenomenological explanation of the observations; and the third a physical explanation of the colors of natural bodies in a series of propositions. This third part too was a direct challenge to Hooke, who had developed his own explanation of the colors of natural bodies in the *Micrographia*. The 1672 version of the "Observations" then proceeds to an incomplete "Hypothesis" to explain the phenomena, whereas the 1675 version ends with the third part and has a much expanded "Hypothesis" as a separate paper.

When the Royal Society asked Newton's permission to publish the papers, he replied to Oldenburg on 25 January 1675/6, "I think it will be best to suspend y^e printing of them for a while because I have some thoughts of writing such another set of Observations for determining y^e manner of y^e production of colours by y^e Prism, w^{ch}, if done at all, ought to precede y^t now in your hands, & will do best to be joyned wth it."[10] On 11 May 1676 he wrote Oldenburg that he still hoped to be able to get some time in the summer to write this new treatise "about y^e colours of y^e Prism".[11]

Newton was evidently now planning a work very much like the *Opticks*, consisting of a "discourse about y^e colours of y^e Prism" (corresponding to Book I) to be followed by the "Observations" on the colors of thin films that he had just sent to the Royal Society. This projected work meant that he had definitively abandoned plans to publish his *Optical Lectures*. For his new work, he intended to omit the mathematical part altogether and to rewrite the part on color extensively. Since Newton did not explain why he made this decision, one can only conjecture. The debate over the "New theory" with Hooke, Huygens, and others had compelled him to recognize that significant parts of his theory of color had to be recast and more rigorously formulated and demonstrated, which would have required a significant revision of the *Lectures*. He must also have recognized that the mathematical part of the work, much of it based on an untested hypothesis, did not lead to a viable mathematical theory of color. Newton apparently began his new work in 1676 with the light revision that is evident in the manuscript of the "Observations" and then set it aside. Since Newton essentially followed the plan of 1676 when he seriously started to write the *Opticks* in 1687 or 1688, the origin of the *Opticks* can be dated to the winter of 1675–6. To be sure, the published *Opticks* differs somewhat from this plan—for example, it contains an entirely new part in the second book on the colors of thick plates, a third book on diffraction, and a number of appended queries—but these, as we shall see, were gradually added as Newton wrote and revised his manuscript over a number of years.

Another aborted optical publication of the 1670s remains mysterious. Sometime between 1672 and 1677, most likely closer to the later date, Newton apparently planned to publish an annotated edition of some of his optical papers and

Papers and Letters, pp. 202–35. The 1672 version of the "Observations" is on ff. 519–28. Newton left both versions untitled, so that it has been given various names, including "Newton's second paper on color and light" in *Isaac Newton's Papers and Letters*.

(10) *Correspondence*, 1:414.

(11) Ibid., 2:6.

correspondence with his critics. Almost all that we know of it is from the two surviving sheets of the publication and that the figures had been engraved.[12]

1.2 The Composition of the *Opticks*

In about 1687 or 1688, Newton wrote the "*Fundamentum opticae*" ("The foundation of optics" or "The foundation of the *Opticks*"), which is the first draft of Book I of the published *Opticks*. He started to revise this, but after writing just one page he abandoned Latin and started anew in English, the language in which it was published in 1704.[13] In the published work this forms the two Parts of Book I, but at this time—and until shortly before publication—they were separate Books I and II. The "*Fundamentum*" essentially presents the theory of white light and color that he had developed in his *Optical Lectures* and optical correspondence in the early 1670s. Even though he took these writings as his foundation, he could not simply revise them for the text of the *Opticks*. In the exchanges over the "New theory," Newton gradually clarified his theory, and in a letter to Huygens he reformulated it more rigorously.[14] The composition of Book III (II in the published work) on the colors of thin films and natural bodies was at first much easier, for he simply lightly revised the three parts of the "Observations" from 1675; this comprised Part I through Part III, Proposition 8 of Book III. Newton then had to decide how to conclude the *Opticks*, and this turned out to be no easy matter. He would ultimately add twelve new propositions to Part III (of which the last ten would present the theory of fits), the entire Part IV on thick plates, and a brief concluding Book IV on diffraction together with sixteen appended Queries. Book III, Parts III and IV were essentially complete by February 1692, but diffraction continued to elude Newton, and he did not write the last Book until 1703, shortly before publication. In this section I will follow the division into Books and Parts of the manuscript, unless I explicitly state otherwise. It is, however, a simple matter to convert to the familiar arrangement of the published work with its one less Book: Books I and II became Book I, Parts I and II; and Books III and IV became Books II and III.

Newton's own account of the composition of the *Opticks* in the Advertisement is somewhat vague and not altogether consistent, but we should recognize it as a recollection written about sixteen years after the event. We can assign Books I and II to probably 1687 or 1688, and with more certainty to no later than June 1689. The Advertisement provides a brief history of the work:[15]

> Part of the ensuing Discourse about Light was written at the desire of some Gentlemen of the *Royal Society*, in the Year 1675. and then sent to their Secretary, and read at their Meetings, and the rest was added about

(12) Hall, *All Was Light*, pp. 85–6. I. B. Cohen published a facsimile of the two sheets (containing eight printed pages) that Derek de Solla Price had found in the decayed binding of a book; "Versions of Isaac Newton's first published paper." The sheets contain annotations by Newton on the "New theory."

(13) "Opticae. Liber primus," ff. 302/3, which is a revise of the opening f. 409 of the "*Fundamentum*." The watermark on ff. 302/3 is the same as that on the rest of Books I and II in the final version of the manuscript (stage 1 in Table 1.1), which supports the assumption that Newton turned to the English version right after beginning in Latin.

(14) Newton to Oldenburg for Huygens, 23 June 1673, *Correspondence*, 1:290–5; see also Shapiro, "The evolving structure of Newton's theory."

(15) O_1, p. [iii].

> Twelve Years after to complete the Theory; except the Third Book, and the last Proposition[s] of the Second, which were since put together out of scattered Papers.

The "part" written in 1675 refers to the "Observations" on the colors of thin films and natural bodies that Newton sent to the Royal Society on 7 December 1675. This formed most of Book II (and in this and the next paragraph I will follow Newton's references to the Books of the published work), so that "the rest" refers to Book I, which was written "about" 1687–8. Surely the enterprise was under way by June 1689, when Huygens met with Newton, for he then told Huygens that a work on color would appear.[16]

Newton's remarks about Book II has some gaps: He "since" added twelve new propositions to Part III of Book II, whence I have added the "s" to "Proposition"; and he altogether ignores the new Part IV of Book II. The manuscripts unambiguously show that he added the last ten propositions to the end of Part III all at once. Nonetheless, all the evidence supports the thrust of the account in the Advertisement, namely, that he wrote Book III and the new material for Book II after he had completed Book I and revised the earlier portion of Book II. One significant omission from Newton's account is that he does not say when he revised the "Observations" for the *Opticks* (Book II, Parts I, II, and much of III) perhaps because it went so quickly. I will now attempt to elaborate Newton's recollections.

The manuscript from which the *Opticks* was printed (ff. 17–78, 91–233, and 359, designated *MSO*) was afterwards returned to Newton and is that published here. Newton wrote out about two-thirds of the manuscript himself, and the remainder was written by six other hands. The manuscript consists of 102 sheets of approximately pott size folded in half, i.e., 25 × 15 inches, or 12½ × 15 inches for a single folio. The text is written on only the recto of each leaf, except for later insertions, which are often on the verso. Although many of the sheets have since split in half along their fold, only two leaves were originally half-sheets, and these are later insertions (ff. 160, 218). It is possible to provide a precise sequence for the composition of the various sections of the *Opticks*—and even reasonably certain, absolute dating—using evidence from the manuscript, such as watermarks, page and figure numbers, and handwriting, textual analysis, and Newton's comments about the composition and his correspondence.[17] The seven stages of the composition are summarized in Table 1.1. Newton's drawings for the diagrams in the *Opticks* were not returned to him, so those from the printed first edition were used here. Some of them have been modified somewhat to agree with the text and with related figures in his writings.

Shortly after composing the "*Fundamentum opticae*" in 1687 or 1688, Newton began to revise it. Though he now decided upon English, the text of the *Opticks* begins as a revised translation of the "*Fundamentum*," but with the rewriting that one expects in a later draft. The propositions and experiments were numbered continuously throughout the "*Fundamentum*," but in the *Opticks* Newton now divided them into two Books. At this first stage, after translating and revising the "*Fundamentum*," the *Opticks* consisted of Book I, Propositions 1–6 and Book II, Propositions 1–6, the text of which is essentially identical to that of the same

(16) Huygens to Leibniz, 24 August 1690, Huygens, *Oeuvres completes*, 9: 471.
(17) More detailed evidence for the relative and absolute dating of the composition of the *Opticks* may be found in Shapiro, "Beyond the dating game", and *FPP*, pp. 138–50.

Table 1.1 The Principal Stages of the Composition of the *Opticks*

Stage	Book, Part, and Folios
1	Bk. I, Props. 1–6; Bk. II,[a] Props. 1–6 ff. 304/5, 29–58, 388/9, 470/1, 75–8, 91–114
2	Bk. I, Defs. & Axioms ff. 17–28 – (304/5)[b]
3	Bk. II, Props. 7–11 ff. 115–30
4	Bk. Ill, Pts. I–III, Prop. 10; Bk. IV, Pt. I, Obs. 1–12, Pt. II[c] ff. 131–91, 368/9; 202–5, 381–4, 344/5, 385/6, 306/7, 79–90
5	Bk. I, Props. 6–7, ff. 59–74 – (388/9, 470/1)
6	Bk. Ill, Pt. Ill, Props. 10–20, Pt. IV, Obs. 5–12 ff. 192–201; 206–17 – (368/9, 381–4, 344/5, 385/6, 306/7, 79–90)
7	Bk. Ill, Pt. IV, Obs. 13; Bk. IV with Queries ff. 218, 219–33, 339

Notes: [a]Until shortly before publication, the published Bk. I, Pt. II was Bk. II. Consequently, during the period of composition the published Bk. II was designated Bk. III, and the published Bk. III was then Bk. IV. [b]A minus sign preceding parentheses indicates that the folios within the parentheses were removed. [c]Book IV in this state was dispersed: Part I became Book III, Part IV, and the sheets with Observations 1–5 were carried over into stage 6. Part II was removed from the manuscript for about a decade and then served as the draft for Book IV in stage 7.

propositions in Book I, Parts I and II of the published edition.[18] Only Proposition 6 in Book II, which contains Newton's famous color-mixing circle, was entirely new and not in the "*Fundamentum*" in some form or other. Book I treats unequal refrangibility and Book II color, although the two cannot be strictly separated. Newton's discovery that sunlight consists of rays of unequal refrangibility, which is a quantitative claim, was a major but not a revolutionary one, and it was not resisted in the way that his view of the nature of white sunlight and colors was. Thus, the long Book I on the unequal refrangibility of sunlight prepared (or softened up) the reader for his more radical idea that sunlight consists of rays of different color.[19]

Neither the "*Fundamentum*" nor the *Opticks* at this point began with definitions and axioms as the published work does. These were added shortly afterwards. In the "*Fundamentum*" five definitions were interspersed among the propositions; three of these were shifted and became part of the eight opening definitions in the *Opticks*. Six sheets with the definitions and axioms (ff. 17–28) were inserted in place of the original opening bifolio (ff. 304/5) after the first stage of Books I and II was completed, thereby completing stage 2.[20]

(18) Tables 3.1 and 3.2 correlate all the propositions, experiments, definitions, etc. of the "*Fundamentum*" and *Opticks*.
(19) Shapiro, "Gradual acceptance."
(20) The relatively late composition of the opening definitions and axioms, after much of Books I and II was nearly complete and thus not integrated into the text, can explain what has seemed to

Book I of the *Opticks* was still far from complete. Newton had devoted the "*Fundamentum*" and the *Opticks* as it then stood to formulating, demonstrating, and explicating his theory of color. He had not yet attempted to deduce the explanation of such phenomena as the rainbow or the colors produced by prisms from the principles of his theory of color, as he had earlier in the 1670s. According to his later terminology, he had thus far adopted only the method of analysis to derive the principles of his theory and not that of synthesis or composition. To rectify this omission and complete the theory Newton added Propositions 7–11 to Book II (Table 1.1, stage 3). These eight sheets (ff. 115–30) are mostly in the hand of an amanuensis.

With the addition of these propositions to Book II Newton judged Books I and II to be essentially complete. He had numbered the folios of these Books and moved on to Book III. However, after he had written out a version of Books III and IV (stage 4 in Table 1.1, to which we will return), he returned to Book I and made the last major addition to it, Proposition 7. This addition is more complicated than the others, for it involved adding a new derivation of the sine law of refraction according to the Cartesian model to the end of Proposition 6, while expanding its Scholium into a proposition in its own right. The aim of the Scholium was to show that the chromatic aberration of lenses (the difference of focal lengths for the extreme colors due to their unequal refractions) was as serious an obstacle to their use as he had long claimed. Because of the intrinsic difficulty of the observations, Newton was at first willing to accept a substantial discrepancy between the measured and predicted values of the chromatic aberration (which is proportional to the dispersive power of the glass). The discrepancy nonetheless troubled him, and he set out to eliminate it. He carried out a set of experiments to determine the chromatic aberration of his lens and the dispersive power of his glass prism. This expanded into Proposition 7, "The perfection of telescopes is impeded by the different refrangibility of the rays of light." Newton removed two sheets (ff. 388/9, 470/1) from the manuscript and inserted eight new ones (ff. 59–74) with the derivation for Proposition 6 and most of Proposition 7, thereby bringing him to stage 5 in Table 1.1. The redetermination of the dispersion of glass, which is one of the fundamental parameters of Newton's theory, in Proposition 7 necessitated changes throughout the manuscript, in particular in Book II, Proposition 10, and Book IV, Part I. These changes can explain why there are two Propositions 7 in Book I of the first edition of the *Opticks.* Before he added this Proposition 7, Newton had already squeezed in another brief Proposition 7 on reflecting telescopes on ff. 77/8 in the blank space that remained at what was then the end of Proposition 6 and Book I. In the second edition this mistake was corrected.

By the fall of 1691, before Newton inserted the new ending to Proposition 6 and Proposition 7 in Book I, he had already completed Books III and IV and thus the entire *Opticks.* We can now follow the composition of the second half of the *Opticks* up to its initial finished state, for within a few months he would revise and rearrange these two Books. In briefly recounting the history of the *Opticks* in the Advertisement, Newton did not mention when he revised his "Observations" for

some scholars to be a puzzling feature of the *Opticks.* While appealing to the definitions and axioms as evidence for the mathematical structure of the *Opticks,* they had to concede that Newton scarcely invoked them in the text. See, for example, Peter Achinstein, "Newton's corpuscular query," p. 171, n. 28.

the *Opticks,* probably because the revisions were so minor. He made so few changes in the text that he was able to mark up the holograph of the manuscript from 1675 that he had retained (ff. 501–17) for his amanuensis to copy for the *Opticks.* This formed Book III, Parts I, II, and III, Propositions 1–8. There is reason to believe that Newton undertook this revision in early 1691, give or take about six months. He did not have the text transcribed yet, for he had some problems with Propositions 8 and 9 on the physical cause of the reflection of light. A more serious problem confronting him, though, was in deciding how to end his book. At first, he planned to follow this material with a new fourth book or part on diffraction. The earliest such draft (ff. 371/2) in fact exactly joins the end of the manuscript of the "Observations" that served as the copy text for the manuscript of the *Opticks.* At the same time Newton was also toying with the idea of a speculative "Fourth Book." This was to be more like the later Queries or his earlier "Hypothesis" than the experimentally based account of the rest of the *Opticks.* The various sketches of this projected "Fourth Book" consist of about twenty propositions without proofs on the nature of light and its interactions with bodies and range over such topics as the physical cause of diffraction, the colors of thin films, color harmonies, and vision.[21]

Newton soon reined in his more speculative tendencies and turned to more empirical optical investigations. He continued his experiments on diffraction and also discovered an entirely new phenomenon, colored rings produced in transparent thick plates. These rings are similar to those produced in thin plates ("Newton's rings"), but whereas the latter vanish after the thickness of the film increases beyond about one ten-thousandth of an inch, the former appear in plates orders of magnitude thicker (about 1/4 in). After carrying out an impressive series of experiments and calculations, Newton was able to predict exactly all their appearances by extending his earlier explanation of the colors of thin films. He now decided to end the *Opticks* with an account of his two experimental investigations and composed a Book IV with Part I on the colors of thick plates and Part II on diffraction (which Newton called "inflexion"). He also worked out an ending for Part III: several paragraphs were added to the end of Proposition 8, and two entirely new propositions, 9 and 10 on the nature of reflection and refraction, were added. He considered adding a physical explanation for the origin of the periodic colors of thin films and thick plates by means of the vibrations set up in bodies when light rays fall upon them (ff. 348/9), but he suppressed it, probably because he judged it too speculative. A fair copy of Book III was made by four amanuenses, whereas Newton wrote out Book IV himself. The manuscript to be joined to Books I and II then consisted of ff. 131–91 (Book III, Parts I–III, Proposition 10), ff. 368/9 (the rest of proposition 10), ff. 202–5 (Book IV, Part I, Observations 1–5), ff. 381–4, 344/5, 385/6, 306/7 (Book IV, Part I, Observations 5–12), and ff. 79–90 (Book IV, Part II); this takes us to stage 4 in Table 1.1. The now scattered sheets that constituted Book IV, Part I form one continuous text, which was entitled "The fourth Book of Opticks. The First Part. Observations concerning the reflexions &

(21) See in order of composition ff. 342/1, 337/8, 335/6. I have called these the "Fourth Book" to distinguish them from the experimental Book IV soon to be described. The "Fourth Book" is briefly discussed in *FPP*, pp. 141–3; and a different interpretation is presented in Cohen, "Hypotheses in Newton's philosophy," pp. 179–81; and Westfall, *Force in Newton's Physics*, pp. 379–80; and *Never at Rest*, pp. 521–3.

colours of thick transparent plates." Book IV, Part II, which was later suppressed and removed in its entirety, was entitled "The second Part. Observations concerning the inflexions of the rays of light in their passage by the surfaces of bodies at a distance." This state of the *Opticks* with a Book IV had been unknown to scholars before the 1990s.

The *Opticks* was now complete. If Newton intended to append his queries at this time, there is no evidence whatsoever that he considered this. He did not, however, remain satisfied with the work as it stood. Within six months of the completion of Books III and IV, they were revised and essentially put into their published state. Some of the revisions were prompted by technical problems. He had encountered a five percent difference between the calculated and measured values of the diameters of the rings in thick plates, and it bothered him. Very quickly he traced the source of the error to the values for the intervals, vibration lengths, or "wavelengths" of light that he had been using for twenty years. His redetermination of this fundamental unit necessitated redoing the intricate calculations for Book IV, Part I. Moreover, after Newton had redetermined the dispersion of glass for the new Proposition 7 in Book I (stage 5 in Table 1.1), he also had to change the value for the index of refraction and dispersion throughout the manuscript, including the calculations for the colors of thick plates in Book IV, Part I. The new values for the intervals and index of refraction were introduced simultaneously in revision. The calculations in the initial state of Book IV, Part I were carried out with an index of refraction of 31/20 and in the revision with 17/11, as required by the redetermination in Book I, Proposition 7. We can therefore place the insertion of Propositions 6 and 7 in Book I between the initial completion of Books III and IV and their revision a few months later, that is, between stages 4 and 6 in Table 1.1.

Newton, however, had a more profound reason for revising Book IV, Part I and the end of Book III, Part III. Even before he had completed the first state of Books III and IV, he was struggling with the idea of adding a physical explanation of the cause of the colored rings of thin films and thick plates. From the time that he had control of the phenomena of thick plates, he attributed them to the same cause as thin plates, namely, vibrations in the corpuscles of bodies. But this was too hypothetical to set forth in the *Opticks.* He had already decided once that it was and suppressed a draft for the conclusion of Part III (ff. 348/9) in which he invoked vibrations that are excited in the corpuscles of bodies when light particles fall on them. If the light particles encounter a compression of the vibrations at the second surface, he explained, they tend to be reflected, and if a rarefaction transmitted, thereby accounting for the alternating bright and dark colored rings. In 1675, Newton had set forth this model in great detail in the "Hypothesis" that he sent to the Royal Society to complement his "Observations", which contained only experiments, observations, and explanations deduced directly from them. Following his own methodological dictum, "I shall not mingle conjectures wth certaintyes,"[22] he carefully labelled the conjectural model of vibrations a "Hypothesis" and set it forth in a paper separate from the more certain results of the "Observations."

(22) Newton, "New theory," *Correspondence*, 1:100.