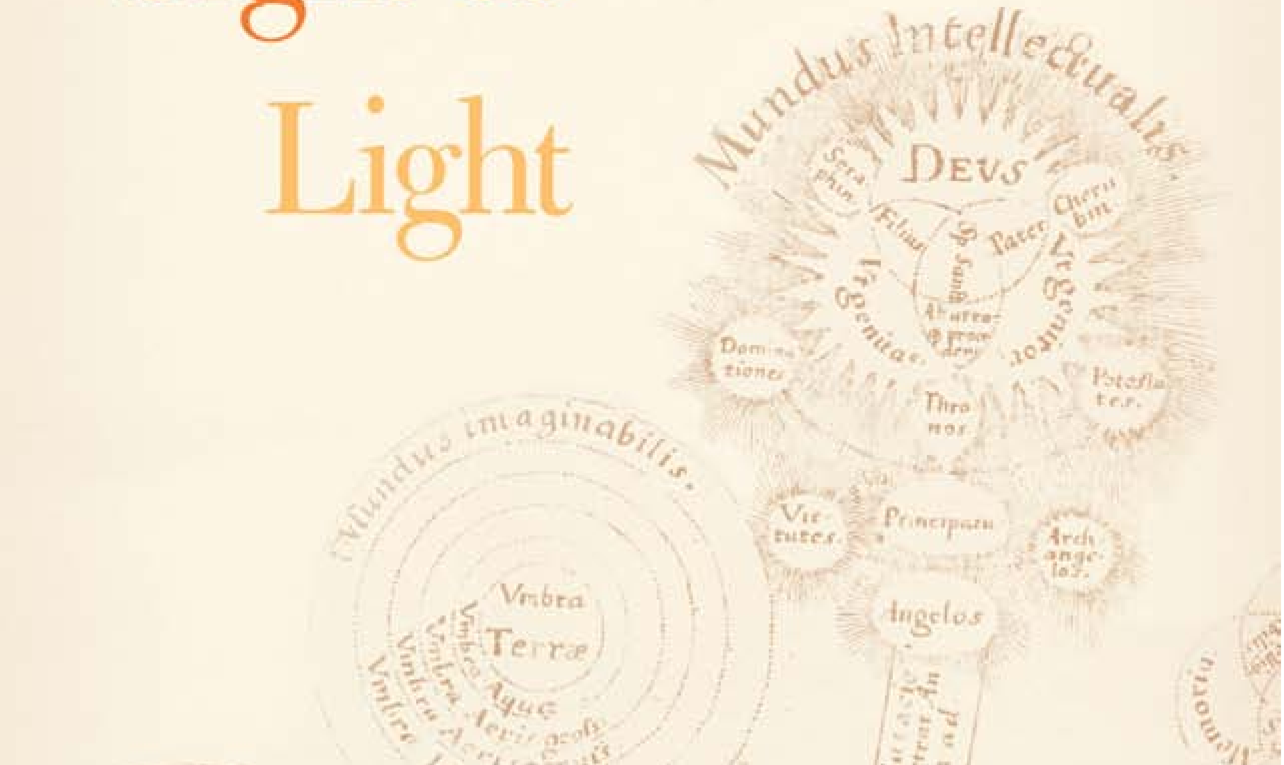
From Sight to Light

THE PASSAGE FROM ANCIENT TO MODERN OPTICS

A. Mark Smith



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PREFACE

The merest glance at any modern optics textbook leaves no doubt that, as currently understood, the science of optics is about light, about its fundamental properties and how they determine such physical behavior as reflection, refraction, and diffraction. But this understanding of optics and its appropriate purview is relatively new. For the vast majority of its history, the science of optics was aimed primarily at explaining not light and its physical manifestations, but sight in all its aspects from physical and physiological causes to perceptual and cognitive effects. Consequently, light theory was not only regarded as subsidiary to sight theory but was actually accommodated to it. And so it remained until the seventeenth century, when the analytic focus of optics shifted rather suddenly, and definitively, from sight to light. Marking the turn from ancient toward modern optics, this shift of focus evoked an equivalent shift in the order of analytic priority. Henceforth, sight theory would become increasingly subsidiary to light theory, the former now accommodated to the latter.

Why this particular turn at this particular time? That is the formative question for this study, and in response I will argue that Johannes Kepler's theory of retinal imaging, which was published in 1604, was instrumental in prompting the turn, as well as in giving it direction and shape, hence my later characterization of the turn as Keplerian. In support of this argument, I will show how Kepler's theory of retinal imaging not only fit within, but also transcended a long-evolving optical tradition that traced back to Greek antiquity via the Muslim Middle Ages. More to the point, I will show how the optical analysis that emerged within this tradition was driven by the need to explain how the visual process can yield a faithful mental picture of physical reality from the initial sensation of light and color. Accordingly, as it developed up to the late Renaissance, the science of optics was expressly designed to vindicate what amounts, quite literally, to a worldview, based on the assumption that objective reality somehow truly conforms to the abstract "image" we have of it in our minds.

After explaining in some detail how this optical tradition evolved between classical antiquity and roughly 1600, I will turn to a close examination of the ways in which Kepler both drew on and—far more importantly—flouted it in advancing his theory of retinal imaging. In the course of this examination, I will argue that it is in this latter respect, as a reaction against tradition and, moreover, a major step toward undermining it, that Kepler's new theory of sight takes on true historical significance. It is also in this respect that by treating the eye as a mere light-focusing device his account of retinal imaging helped spur the shift in analytic focus that marked the turn toward modern optics. Not just a transformation of optics, though, the Keplerian turn entailed an even more profound transformation of worldview, grounded in deep skepticism about whether objective reality is anything like the mental picture we have of it. Well on the way to completion by the end of the seventeenth century, this latter transformation is the subject of the book's concluding chapter, where I will show how it came about in response to certain implications of Kepler's new visual model.

As is evident from the preceding synopsis, this study covers an extraordinarily long chronological span, some two millennia in all. It also covers a broad spectrum of topics that include the physics of radiation, ray geometry, ocular anatomy, neuroanatomy and physiology, psychology, and epistemology. In certain instances, my treatment of these topics is moderately technical. In particular, I have had to deal in some detail with ray geometry and its theoretical underpinnings in order, eventually, to make proper, contextual sense of Kepler's analysis of convex lenses, which forms the linchpin for his account of retinal imaging. I realize that in delving into the intricacies of ray geometry I risk losing readers who find mathematics uncongenial, if not downright nettlesome. Like the devil, however, Clio is sometimes in the details, and in this case the details are too historically significant to avoid. Still, I have done my best to minimize them while explaining them in the simplest terms possible, all in the hope of making them understandable to any educated and willing reader, no matter how skimpy his or her technical or mathematical background. I am, in short, aiming as much at interested generalists as I am at specialists in the history of science.

Given the chronological and topical scope of this study, I have had to venture into nooks and crannies of scholarship that lie well outside my comfort zone. Who am I, a historian of medieval science, after all, to pontificate on classical Greek and late antique philosophy, early Muslim educational ideology, medieval Christian speculative theology, or Renaissance art, all of which crop up in the course of this study? Fortunately, while I was in the throes of writing this book, I managed to persuade several suitably knowledgeable friends and colleagues to give relevant chapters a close, critical scrutiny and thus, I trust, keep me from straying too far from the acceptable bounds of fact or interpretation. For this service I warmly thank, in alphabetical order: Alan Bowen, Sven Dupré, Jeremiah "Jerry" Hackett, George Hand, Jon McGinnis, Mary Quinlan-McGrath, and Yaakov Zik. Special thanks, finally, to Robert Hatch not only for carefully vetting the portions of the study that deal with the late Renaissance and early modern periods, but also for casting a gimlet eye over the entire manuscript to root out mistakes of fact or interpretation, as well as infelicities of style.

CHAPTER 1

Introduction

First published by the University of Chicago Press in 1976 and reissued in 1981, David Lindberg's *Theories of Vision from al-Kindi to Kepler* has stood to this day as the definitive study of pre-Keplerian optics and its historical evolution. The reasons are not far to seek. For one thing, that study is based on impeccable scholarship; Lindberg delved deeply and broadly into the appropriate primary and secondary sources available to him at the time. Crucial among these sources was a small group of late thirteenth-century "perspectivist" optical writers who drew heavily upon the Latin version of Ibn al-Haytham's *Kitāb al-Manāẓir* ("Book of Optics"). Probably completed by 1030, this treatise was rendered from Arabic into Latin sometime around 1200 under the title *De aspectibus* and attributed to "Alhacen."[1]

Another reason for the continuing success of Lindberg's study is his gift for clarity and precision in both thought and articulation, a gift that is evident in the deceptively simple, linear way he framed his narrative. Picking up the threads of his analysis in Greek antiquity, Lindberg showed in admirable detail how they were unraveled, modified, and augmented over the succeeding centuries until Johannes Kepler finally managed to weave them together into a coherent whole at the turn of the seventeenth century. Moreover, the narrative

1. In the actual manuscripts of the Latin version of the *Kitāb al-Manāẓir*, Ibn al-Haytham is most often referred to by the Latin transliteration "Alhacen" of his given name "al-Ḥasan" (Abū ʿAlī al-Ḥasan ibn al-Ḥasan ibn al-Haytham). The work itself is most often titled *De aspectibus*. The forms "Alhazen" of his name and *Perspectiva* for the title of the work are later accretions. For discussion of these points, see A. Mark Smith, *Alhacen's Theory of Visual Perception* (Philadelphia: American Philosophical Society Press, 2001), xxi.

itself is compellingly thesis driven; Lindberg argued clearly and forcefully that Kepler's theory of retinal imaging in the *Ad Vitellionem Paralipomena* ("Supplement to Witelo") of 1604 represented not a fundamental break with, but rather a continuation of the perspectivist optical tradition as it evolved over the later Middle Ages and Renaissance. Lindberg made no bones about it: "Kepler was the culminating figure in the perspectivist tradition"; and Lindberg's analysis leads us systematically and inexorably to concur with this point.[2]

While thus emphasizing the centrality of perspectivist optics in the development of Kepler's visual model, Lindberg also showed that the theoretical foundations of those optics are as sophisticated as they are systematic and coherent. In other words, *pace* T. S. Kuhn, perspectivist optics provided what amounts to a scientific paradigm during the later Middle Ages and Renaissance.[3] Furthermore, Lindberg made it eminently clear that pre-Keplerian optics was not focused narrowly on the physical analysis of light and color but dealt more broadly with issues of visual perception. In order to be properly understood, then, pre-Keplerian optics had to be analyzed within this broader context because light theory and sight theory were interdependent before the seventeenth century—hence the focus on "vision" rather than "light" in the title of Lindberg's study.[4]

That no one has yet offered a compelling alternative to Lindberg's account is a testament to its coherence and persuasiveness.[5] Yet over the past three de-

2. Quotation from David Lindberg, *Theories of Vision from al-Kindi to Kepler* (Chicago: University of Chicago Press, 1976), 207. It is worth noting that Lindberg was arguing against the prevailing view of the time, championed most notably by Alexandre Koyré, that early modern science marked a revolutionary departure from its medieval forebear. Today, of course, the notion of an early modern scientific revolution has been, if not discredited, then modified considerably; see, e.g., Stephen Shapin, *The Scientific Revolution* (Chicago: University of Chicago Press, 1996), for one of the more radical reactions to this notion.

3. For Thomas S. Kuhn's claim that there was no optical paradigm before the end of the seventeenth century, see *The Structure of Scientific Revolutions*, 2nd ed. (Chicago: University of Chicago Press, 1970), 12–13.

4. In this regard Lindberg was reacting against Vasco Ronchi's *Storia della luce* ("History of Light") of 1939, which was translated into English by V. Barocas as *The Nature of Light* (Cambridge, MA: Harvard University Press, 1970). Lindberg intended his *Theories* as a corrective to Ronchi's study, which Lindberg considered to be riddled with factual errors and misconceptions; see his review: "New Light on an Old Story" (essay review of Vasco Ronchi, *The Nature of Light: An Historical Survey*, trans. V. Barocas [Cambridge, MA: Harvard University Press, 1970]), *Isis* 62 (1971): 522–24.

5. To be sure, books dealing with the development of optics have appeared since Lindberg published his *Theories*. Two fairly recent examples are David Park, *The Fire within the Eye:*

cades a considerable amount of work, some of it revisionary, has been done on pre-Keplerian optics. New texts have been brought to light, Roshdi Rashed's studies of previously unknown or little-known medieval Arabic sources being especially noteworthy in this regard.[6] Old texts have been critically edited or reedited, translated, and closely analyzed. Abdelhamid I. Sabra's work on the Arabic text of Ibn al-Haytham's *Kitāb al-Manāẓir* and mine on its medieval Latin counterpart, Alhacen's *De aspectibus*, serve as related examples.[7] New interpretive avenues have also been opened. Katherine Tachau, for instance, has shown how deeply implicated perspectivist theory was in later medieval discussions of epistemology, and recent work on "practical" optics in the sixteenth century, particularly the study of mirrors and lenses, has shed light not only on the scientific milieu within which Kepler conducted his optical

A Historical Essay on the Nature and Meaning of Light (Princeton, NJ: Princeton University Press, 1997); and Mark Pendergrast, *Mirror Mirror: A History of the Human Love Affair with Reflection* (New York: Basic Books, 2003). It is no derogation to these books, however, to say that neither is, or purports to be, a work of serious historical scholarship. Both are written by nonspecialists in the field (Park is a physicist and Pendergrast a journalist), both are pitched at a fairly popular level, and neither engages with historiographical or interpretive issues; see, e.g., my review of Park in *Physics Today* 51 (1998): 62–63. Even more recent, and more scholarly in its focus, is Olivier Darrigol's *A History of Optics from Greek Antiquity to the Nineteenth Century* (Oxford: Oxford University Press, 2012), but he devotes only thirty-six pages to the development of optics from Greek Antiquity to Kepler, and his treatment of pre-Keplerian optics is mostly derivative.

6. See, e.g., Roshdi Rashed, *Géométrie et dioptrique au X^e siècle* (Paris: Les Belles Lettres, 1993).

7. So far Sabra has published critical Arabic editions of the first five of the seven books comprising the *Kitāb al-Manāẓir* in *The Optics of Ibn al-Haytham. Books I-II-III: On Direct Vision* (Kuwait: National Council for Culture, Arts, and Letters, 1983) and *The Optics of Ibn al-Haytham. An Edition of the Arabic Text of Books IV–V: On Reflection and Images Seen by Reflection* (Kuwait: National Council for Culture, Arts, and Letters, 2002). In addition, he has published a two-volume English translation of the first three books in *The Optics of Ibn al-Haytham: Books I–III on Direct Vision* (London: Warburg Institute, 1989). For my critical editions and translations of all seven books of the *De aspectibus*, see *Alhacen's Theory of Visual Perception* (Philadelphia: American Philosophical Society Press, 2001); *Alhacen on the Principles of Reflection* (Philadelphia: American Philosophical Society Press, 2006); *Alhacen on Image-Formation and Image-Distortion in Mirrors* (Philadelphia: American Philosophical Society Press, 2008); and *Alhacen on Refraction* (Philadelphia: American Philosophical Society Press, 2010). For a recent edition and French translation of book 7, see Paul Pietquin, *Le septième livre du traité* De aspectibus *d'Alhazen, traduction latine médiévale de* l'Optique *d'Ibn al-Haytham* (Louvain: Académie royale de Belgique, 2010).

research but also on the conceptual and methodological basis of that research.[8] In addition, the relationship between Renaissance art and perspectivist optics has been reexamined and, in some cases, reconfigured since Lindberg's day.[9]

Although none of these developments, singly or collectively, calls for an outright rejection of Lindberg's account, they do call for a significant revamping of it. That is what I propose to do in this study. I say "revamping" because Lindberg's account will serve as the backbone of my own in terms of factual detail (or most of it), as well as basic lineaments. Accordingly, the cast of main characters will remain essentially the same, although the roles of some will change. Ptolemy, for example, will play a far more important part in my narrative, and Alhacen's place in that narrative will be significantly altered by my linking him more tightly to Ptolemy and more loosely to Kepler than Lindberg did.

There will be some changes in emphasis, as well. One such change centers on Lindberg's eschewal of psychological and epistemological issues in order that his "investigation [not] get out of hand." To be sure, he acknowledged, such issues were "often raised within the context of visual theory," but they "were never its central concerns."[10] Long at odds with Lindberg over this point, I see these concerns as, if not absolutely central, then certainly integral to the formation of visual theory, and thus optics in general, from antiquity right up to the time of Kepler.[11] In fact, I will argue that perspectivist optics was expressly designed with these concerns in mind. Thus, whereas Lindberg's analysis effectively stops at the back of the eye, mine will trace the entire perceptual process from eye to brain, from the lowest-level apprehension of visible radiation to the conceptual and intellectual grasp of its object sources. Another change in emphasis involves reflection and refraction. I think Lindberg gave these two phenomena far shorter shrift than they merit because I am convinced that sixteenth-century efforts to understand reflection from concave mirrors and refraction through convex lenses played a crucial, perhaps determinative role in Kepler's model of retinal imaging. I will therefore pay closer attention

8. See, e.g., Katherine Tachau, *Vision and Certitude in the Age of Ockham* (Leiden: Brill, 1988); Sven Dupré, "Ausonio's Mirrors and Galileo's Lenses: The Telescope and Sixteenth-Century Practical Optical Knowledge," *Galileiana* 2 (2005): 145–80; and Eileen Reeves, *Galileo's Glassworks* (Cambridge, MA: Harvard University Press, 2008).

9. See, e.g., David Summers, *The Judgement of Sense* (Cambridge: Cambridge University Press, 1987).

10. Lindberg, *Theories of Vision*, x.

11. See, e.g., A. Mark Smith, "Getting the Big Picture in Perspectivist Optics," *Isis* 72 (1981): 568–89.

than Lindberg did to how these two phenomena, especially refraction, were understood and analyzed from antiquity to the seventeenth century.

This increased emphasis on reflection and refraction requires a somewhat more extensive discussion of ray theory and its mathematical underpinnings than Lindberg offered. Consequently, I have devoted significant portions of chapters 2 and 3 to showing how the foundations of that theory were laid in classical antiquity and how the ray geometry at its heart was used to explain a spectrum of optical phenomena from size perception to image formation in variously shaped mirrors. I have, however, tried to keep the ray-theoretical analysis in those chapters to a focused minimum aimed at providing the necessary background, and no more, for the discussion of spatial perception, reflection, and refraction in later chapters. I have also simplified that analysis as much as possible by taking a relatively superficial, descriptive approach to the mathematics on which it is based so as not to get entangled in the details of proof. I have therefore done my best to make at least the gist, if not the technical details, of that analysis accessible to any patient and attentive reader, no matter how math averse.

These are just some of the more salient revisions I will be making to Lindberg's account. But the most marked difference between my account and his resides in our respective views of Kepler's visual model and its relationship to perspectivist theory. Lindberg stressed continuity in that relationship. I, on the other hand, will emphasize discontinuity by arguing that Kepler's theory of retinal imaging did represent a break, a radical break, with the perspectivist tradition. This break, I will show, occurred at two levels. First, Kepler's theory of retinal imaging put the perspectivist visual model in jeopardy by severing the perceptual and epistemological link between eye and brain the perspectivists so carefully forged. As a result, the study of light was increasingly dissociated from the study of sight in post-Keplerian optics, as it evolved over the seventeenth century. The consequent shift of analytic focus from sight to light between roughly 1600 and 1700 constitutes what I call the Keplerian turn, and it is this turn, not Kepler himself, that is the ultimate focus of this book. Second, Kepler's analysis of convex lenses, which was central to his theory of retinal imaging, depended on theoretical and methodological concepts that were nowhere to be found in the perspectivist sources available to him. In certain key respects, in fact, he succeeded in that analysis despite rather than because of what he could have gleaned from those sources. I am not, I hasten to add, suggesting that Kepler's model of retinal imaging was a *creatio ex nihilo*. There is no question that he constructed that model on perspectivist foundations, but in the process he undermined those foundations in radical and ultimately lethal ways. In short, perspectivist optics served more as a foil than as a springboard for Kepler.

Significant though they are, these differences should not mask the fundamental points of agreement between Lindberg's account and my own. Both have as an ultimate goal to explain Kepler's theory of retinal imaging in proper historical context, although I will follow some of the ramifications of that theory into the seventeenth century, as they eventuated in the Keplerian turn. Both take perspectivist optics as a central component of that context. Both follow similar narrative paths, tracing the evolution of pre-Keplerian optics from Greek antiquity, through the Arabic Middle Ages, into the Latin Middle Ages and Renaissance. Both acknowledge Alhacen as a pivotal figure in the transition from classical Greek to medieval optics. Both recognize that pre-Keplerian optical theory was oriented toward the analysis of light *and* vision, not light alone. And both take a decidedly thematic or conceptual approach. At bottom, then, my aim here is not so much to supplant as to supplement Lindberg's account.

At this point, I should briefly explain what I intend to do in the following chapters and how I propose to do it. To start with, I make no claims to writing a comprehensive, global history of optics from antiquity to the seventeenth century.[12] My approach will be considerably more focused and thematic than that because, like Lindberg's, my narrative path leads more or less directly to and through Kepler and is thus pretty restrictively goal oriented. Hence, I will pay scant attention, if any, to various bypaths along the way that do not loop back to the main track leading toward Kepler. This is not to say that such bypaths are uninteresting or insignificant; they are simply irrelevant to my purposes. The medieval "Arabic" optical tradition serves as a prime

12. The recently revived push toward a global approach to the history of science is reflected in the five essays by Marwa Elshakry, Helen Tilley, Shruti Kapila, Neil Safier, and Sujit Sivasundaram in the "Focus" section of *Isis* 101 (2010): 95–158. See especially Marwa Elshakry, "When Science Became Western: Historiographical Reflections," 98–109. This global approach calls for a radical loosening of the definitional constraints on "science" posed by rigid "Western" scientific norms in order to give non-Western cultures their due in the development of scientific thought. Presumably, this should eventuate in a grand, global synthesis, but in adverting to "the fantasy of a singular global history," Sivasundaram seems to doubt that it will; see p. 95. For a fairly recent example of such a "global" approach, see Arun Bala, *The Dialogue of Civilizations in the Birth of Modern Science* (New York: Palgrave Macmillan, 2006); cf. Edward Grant, "Reflections of a Troglodyte Historian of Science," *Osiris* 27 (2012): 133–55, for a critical evaluation of Bala's approach.

example.[13] That it, like its medieval Latin counterpart, was firmly rooted in Greek sources is beyond question, as is the fact that several key Arabic thinkers—Alhacen foremost among them—were instrumental in the development of optics in the medieval Latin West. But to concentrate on these figures alone is to ignore some truly interesting and innovative optical work carried out in the medieval Muslim world.

Take the tenth-century mathematician Ibn Sahl (d. ca. 1000) associated with the ʿAbbāsid court in Baghdad. In the course of analyzing curved mirrors and lenses in his *On Burning Instruments*, he provided an elegant and ingenious mathematical demonstration of the focusing property of hyperboloidal lenses based on what amounts to the sine law of refraction.[14] As far as we know, Ibn Sahl's version of that law predates the earliest European version, generally attributed to Willibrord Snel, by more than six centuries. So too, as far as we know, it would take well over six centuries before anyone in Europe undertook an equivalent analysis of hyperboloidal lenses.[15] Why, then, not include Ibn Sahl as an integral part of my narrative? Because, not having been translated into a European language until very recently (by Roshdi Rashed), his *On Burning Instruments* remained unknown in the Latin West. There is, in short, no evidence whatever that Ibn Sahl had anything to do with the sine law arrived at by Snel. Examples like this abound of brilliant and innovative Arabic thinkers, such as Kamāl al-Dīn al-Fārisī (d. 1318), whose optical work

13. An abiding problem for anyone dealing with science in the Muslim world is how best to denominate it according to kind. I have chosen the linguistic characterization "Arabic" in order to avoid not only the religious overtones of "Muslim" or "Islamic" but also the ethnic overtones of "Arabian." Many early contributors to Arabic science were neither Muslim nor Arab, yet Arabic did serve as the lingua franca for scholarship throughout the medieval Muslim world. Marshall Hodgson's "Islamicate" might perhaps be better in view of its cultural connotations, but I decided against it because it is somewhat clumsy and has never achieved widespread usage.

14. See Roshdi Rashed, "A Pioneer in Anaclastics: Ibn Sahl on Burning Mirrors and Lenses," *Isis* 81 (1990): 464–91. Simply put, the sine law states that when light is refracted in passing from one transparent medium to another, the sines of the angles of incidence and refraction will be in constant proportion, which is to say that for all angles of incidence, sine i / sine r = constant. Accordingly, in figure 9.2 (see chapter 9), if angles of incidence KBM and ABH yield angles of refraction NBL and NBI, respectively, then KBM / NBL = ABH / NBL = constant.

15. Although Snel is generally credited with having "discovered" the sine law sometime around 1620, the Englishman Thomas Harriot arrived at it by no later than 1602 and perhaps as early as the late 1590s. René Descartes was the first to publish the sine law, along with a specious proof, in his *Dioptrique* of 1637, where he also demonstrated the focusing property of hyperboloidal lenses.

developed along byways that never looped back to my main track and to whom I will therefore give little more than lip service.[16]

One unavoidable consequence of my taking this tack is that the resulting narrative will have a definite "Western" slant. That such a slant smacks of Edward Said's "Orientalism" hardly needs saying.[17] After all, as far as the development of modern optics goes (via Kepler), some of the most innovative and forward-looking Arabic thinkers play little or no part whatever in my narrative. I can thus be accused of treating the development of modern optics Eurocentrically, as a uniquely "Western" phenomenon to which the "West" can claim exclusive proprietary rights.[18] One of the most prominent recent critics of such a culturally isolationist view of science is George Saliba, who poses the rhetorical question, "Whose science [is] it . . . anyway?"[19] His an-

16. Author of the *Tanqīḥ al-Manāẓir* ("Revision of [Alhacen's] Optics"), Kamāl al-Dīn al-Fārisī made significant adjustments to and elaborations on Alhacen's optical work. He was a student of the renowned mathematician and astronomer, Quṭb al-Dīn al-Shīrāzī, who in turn was a student of Naṣīr al-Dīn al-Ṭūsī, founder of the Maragha observatory in 1259 under the Mongol il-khan Hulagu.

17. Edward Said, *Orientalism* (New York: Parthenon, 1978). In light of Said's scathing attack on Eurocentric views of the "East" as undifferentiated and backward, I will bracket "East" with quotation marks in recognition of its problematic conceptual status. After all, the medieval Muslim "East" extended through North Africa into Spain at the far western reaches of Europe. I will do the same with "West," which, ironically enough, Said presents as monolithic in its arrogance and its push for dominance, all the while demanding that "Westerners" develop a more nuanced and sympathetic approach to the "East."

18. As Roshdi Rashed puts it, "scientific activity outside of Europe, poorly integrated into the history of science, is the object of an anthropology of science whose academic translation is nothing more than Orientalism," in *The Development of Arabic Mathematics: Between Arithmetic and Algebra* (Dordrecht: Kluwer Academic, 1994), 333.

19. Saliba poses this question at the end of a long essay titled "Whose Science Is Arabic Science in the Renaissance" on his website (http://www.columbia.edu/~gas1/project/visions/case1/sci.5.html). His main point is that to isolate science according to cultural categories, such as Islamic, Western, Greek, is both futile and hegemonic in the context of the "grand narrative" of triumphal modern Western science. In his recent *Islamic Science and the Making of the European Renaissance* (Cambridge, MA: MIT Press, 2007), Saliba attempts to demonstrate this point by showing that in order to account for technical details of planetary motion in the *De revolutionibus*, Copernicus borrowed certain analytic devices from a trio of medieval Muslim astronomers, two of whom had been ensconced at the observatory of Maragha. That being the case, we are forced to ask whether the so-called Copernican revolution was actually "Copernican" and, therefore, whether it was meaningfully "Western." Cf., however, the reviews by Toby Huff, in *Middle East Quarterly* 15 (2008): 77–79, and Owen Gingerich, in *Journal of Interdisciplinary History* 39 (2008): 310–11.

swer, of course, is that science belongs to everyone, to every culture; any claim to ownership within a particular culture is thus hegemonic. In principle I agree with Saliba; it would be difficult for me not to, having spent over a quarter of a century closely studying Alhacen's optics. But in historical practice I find his open stance problematic because it is based on what I view as an unwarranted absolutism according to which a given "science" or scientific concept remains temporally and culturally constant or atomic.

Let us go back to the sine law for a moment. If we take that law as factually determinate, and if we think in terms of temporal priority alone, then the sine law obviously belongs to Ibn Sahl and, by extension, the Arabic "East." But to take the sine law in that way, as a brute scientific fact, or at least a declaration of scientific fact, is naively reductionist. As the French phrase *les faits sont faits* sums it up nicely, facts may be facts, but they are also constructed. Indeed, as recent sociologists of scientific knowledge would have it, they are *socially* constructed.[20] Consequently, if we place Ibn Sahl's and Snel's versions of the sine law in their respective "marketplace of ideas," they take on an entirely different cast. Whereas there appear to have been no buyers in Ibn Sahl's marketplace, there was a brisk trade in Snel's.[21] It was therefore in the "West," not the "East," that the sine law became historically significant and meaningful because it was there that it became communal and therefore fruitful.

The same holds for the evolution of modern optics over the sixteenth and seventeenth centuries. It may well be that certain key ideas, laws, and concepts that contributed to that evolution were anticipated by Arabic or, for that matter, Indian, Chinese, or Mesoamerican thinkers. And it is certainly the case that there was a lively cross-cultural marketplace of commodities and ideas between the Latin "West" and Arabic "East" throughout the Middle Ages and Renaissance. The fact remains, though, that it was in Europe that those ideas, laws, and concepts were eventually assimilated, refined, channeled, and combined in such a way as to form the basis for what most of us today would characterize as modern optics. Any claim to the contrary strikes me as historically perverse. Furthermore, to contend that the evolution of modern optics over the

20. For an extreme defense of social construction, see Stephen Shapin, *A Social History of Truth* (Chicago: University of Chicago Press, 1994); for a more moderate one, see Stephen Shapin and Simon Schaffer, *Leviathan and the Air Pump* (Princeton, NJ: Princeton University Press, 1989).

21. That Alhacen did not adopt Ibn Sahl's law is particularly telling as an indication of its failure to influence Arabic optics; for a discussion of this point, see Smith, *Alhacen on Refraction*, lxxxii–lxxxiv. That the sine law became a staple of optical analysis in seventeenth-century Europe is so obvious it needs no belaboring.

sixteenth and seventeenth centuries happened in Europe is not to give Europe proprietary rights to that science or to accord Europe cultural exceptionalism or superiority for having developed it. I therefore strongly resist any charge of being trapped, whether wittingly or unwittingly, in some grand, master narrative or of engaging in hegemonic discourse. I do, however, freely acknowledge that I will be telling a particular story, not necessarily the whole story, nor the "true" story, nor the only story, nor even the best story. I also acknowledge that my story is framed within a specific historiographic or metahistorical tradition in which historical narratives have a beginning, middle, and end.[22]

No less selective than the narrative path I intend to follow is the set of landmarks I will use to define it. Those landmarks will be primarily textual because, as I mentioned earlier, my approach will be thematic or conceptual rather than *événementielle* (to borrow from Fernand Braudel) or prosopographical. Its primary focus will therefore not be on events or personalities. As might be expected, the core of the textual sources used in this study will comprise works devoted wholly or in great part to the systematic analysis of visual theory, light and color, or both. Euclid's *Optics* and *Catoptrics*, Alhacen's *De aspectibus*, Roger Bacon's *Perspectiva*, and Kepler's *Paralipomena* are obvious examples. Aristotle's *De anima*, Galen's *De usu partium*, and Avicenna's *Shifā* ("Healing") are perhaps less obvious but no less representative examples.

Secondary, but by no means marginal, will be artifactual sources that provide relevant technological information. Glass looms large in this respect because a variety of optical theorists from Ptolemy and Alhacen onward based, or at least claim to have based, empirical studies of refraction on the passage of visual rays or light rays through it. The type and quality of the glass available to those theorists has an obvious bearing on the feasibility or accuracy of these studies and their purported results. Lenses are more problematic. Lens-like objects dating back well before 1500 BC have been uncovered and closely analyzed for optical properties, and it is tempting on that basis to suppose they were used as magnifying devices for close work or viewing.[23] Unfortunately, there is no way of determining whether they were actually intended for such use or any way of knowing whether they were produced with any optical principles, either pragmatic or theoretical, in mind. For that reason, these artifacts

22. See Hayden White, "The Value of Narrativity in the Representation of Reality," in *The Content of the Form* (Baltimore: Johns Hopkins Press, 1987), 1–25.

23. See, e.g., Jay M. Enoch, "The Enigma of Early Lens Use," *Technology and Culture* 39 (1988): 273–91.

cannot be meaningfully included in a history of optics or, for that matter, a history of lenses. From my narrative perspective, which is admittedly conservative, that history will only begin to take shape during the Greco-Roman period.

I am well aware of the potential shortcomings and pitfalls of such a conceptual, text-based approach. It is all too easy, for instance, to treat concepts or ideas as having a life of their own without due consideration of how they were assimilated and modified over time and place. Thus one might assume incorrectly that "ray" meant the same thing for Euclid as it did for Alhacen or Descartes insofar as all three took it as rectilinear and therefore geometrically representable by a straight line. It is also easy to view similarity of concepts or ideas as an indication of influence. On that basis one might be led to suppose, again incorrectly, that Snel somehow got the sine law from Ibn Sahl either directly or through connected, intermediary sources as yet unknown. Moreover, the kinds of texts upon which my study is based are finished products whose actual manufacture we know little or nothing about. As a result, these texts provide almost no information about the scholarly networks—the marketplace of ideas, if you will—within which they were produced and disseminated. Early in the *De aspectibus*, for instance, Alhacen divides contemporary and antecedent optical theorists into two main groups: mathematicians (*mathematici)* and natural philosophers (*naturales*). Precisely whom he had in mind is impossible to say with any certainty because he gave no names.[24] The best we can do is make educated guesses, and tentative ones at that. Nor is Alhacen unique in this regard; most of the pre-Keplerian optical theorists I will deal with in the course of this study (Roger Bacon being a salient exception) were equally reticent about citing sources. As a result, the social dimension of my narrative will be severely but necessarily limited.

A further limitation is imposed according to the time period my study spans and the relative scarcity of sources and types of sources available for most of it. Especially acute for antiquity, this scarcity has a variety of causes. First and most obvious is loss over time due to natural deterioration, fire, earthquake, flooding, and so on. The fate of the Alexandrian "library" in successive holocausts between the first century BC and the seventh century AD is a clear case in point.[25] Second is supersession. Certain works, such as Euclid's *Elements* and Ptolemy's *Almagest*, assumed such canonical status that earlier works

24. For a brief discussion of this point, see Smith, *Alhacen's Theory*, xxv.

25. See Diana Delia, "From Romance to Rhetoric: The Alexandrian Library in Classical and Islamic Traditions," *American Historical Review* 97 (1992): 1449–67.