Technology and/as Theory:
Material Thinking in Ancient Science and Medicine

Colin Webster

Submitted in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy
in the Graduate School of Arts and Sciences

COLUMBIA UNIVERSITY

2014

ABSTRACT

Technology and/as Theory:
Material Thinking in Ancient Science and Medicine

Colin Webster

Multiple natural philosophers in antiquity proposed that nature possessed considerable technical skill. Yet, the specific conceptual implications of this assertion were quite different in fourth century BCE Athens—with its pots, bronze tools and cisterns—than in second century CE Rome—where large-scale aqueducts, elaborate water machines and extensive glassworks were commonplace. This dissertation assesses the impact that these different technological environments had on philosophical and scientific theories. In short, it argues that contemporary technologies shaped ancient philosophers' physical assumptions by providing cognitive tools with which to understand natural phenomena. As a result, as technologies evolved—even in relatively modest ways—so too did conceptual models of the natural world. To explore these assertions, this dissertation focuses on two main fields of explanation, the vascular system and vision, and includes investigations of such technologies as pipes, pumps, mirrors, wax tablets, diagrams and experimental apparatuses. It demonstrates the ways in which scientific theorists use the specific material technologies around them as heuristics to conceptualize physical processes.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS p. iii

INTRODUCTION: TECHNOLOGICAL ANALOGIES AND PHYSICAL HEURISTICS

Introduction: Theories and Things p. 1

0.1 Analogies and Heuristics p. 8

0.2 Science, Technology and τέχναι p. 12

0.3 Divine Demiurge and Nature as a Technician p. 17

0.4 (Technological) Analogies as a Scientific Method p. 22

0.5 Chapter Outline p. 27

CHAPTER ONE: THE VASCULAR SYSTEM AND WATER TECHNOLOGIES

1.0 Introduction: Technologies as Heuristics p. 30

1.1 Technological Analogies as Technological Metonyms p. 31

1.2 Dual Function Blood Vessels and Modal Heuristics p. 42

1.3 Aristotle's Heart and Competing Heuristics p. 56

1.4 Conclusion p. 67

CHAPTER TWO: PNEUMATICS, AQUEDUCTS AND THE PRESSURIZED BODY

2.0 Introduction: Alexandria and Rome p. 69

2.1 The Pump and the Pressurization of the Body p. 71

2.2 Asclepiades of Bithynia and Cultural Heuristics p. 92

2.3 Conclusion p. 113

CHAPTER THREE: THE MATERIAL TECHNOLOGIES OF VISION

3.0 Introduction: A Technological History of Vision p. 115

3.1 Cognitive Attraction and Empedocles' Lamp p. 118

3.2 Cognitive Focus and the Mirror p. 132

3.3 Layered Heuristics: Democritus' Mirrors and Wax Tablets p. 140

3.4 Aristotle, Image-Transfer and the Wax of Memory p. 157

3.5 Conclusion p. 170

CHAPTER FOUR: OPTICAL DIAGRAMS AS PHYSICAL HEURISTICS

4.0 Diagrams as Physical Heuristics p. 172

4.1 Aristotle's Optics p. 173

4.2 Euclid's *Optics* and Hybrid Ontology p. 189

4.3 The Visual Cone and Geometrical Astronomy p. 202

4.4 Euclid's *Optics* and Constructing Appearances p. 209

4.5 Conclusion p. 218

CHAPTER FIVE: VISUAL AND GEOMETRICAL APPARATUSES

5.0 Introduction: Experimental and Cognitive Tools p. 220

5.1 Ptolemy's *Optics* p. 221

5.2 Ptolemy's Ruler and the Visual Axis p. 231

5.3 Ptolemy's Anatomical Geometry p. 237

5.4 Galen's Geometrical Anatomy p. 244

5.5 Galen's Triangular Axes and Double Vision p. 259

5.6 Galen's *Libella* p. 266

5.7 Conclusion p. 269

CONCLUSION: TECHNOLOGY AND THE TOOL BOX

6.0 Looking Backwards and Forwards p. 271

WORKS CITED p. 275

LIST OF ILLUSTRATIONS

Fig. 1 An image of a *clepsydra* device p. 32

Fig. 2 Diel's Interpretation of Empedocles' *clepsydra* (cutaneous breathing) p. 35

Fig. 3 Furley's Interpretation of Empedocles' *clepsydra* (cutaneous and mouth/nose breathing) p. 37

Fig. 4 Booth's Interpretation of Empedocles' *clepsydra* (nose breathing) p. 38

Fig. 5 O'Brien's Interpretation of Empedocles' *clepsydra* (mouth/nose breathing) p. 39

Fig. 6 Terracotta Pipes of the Peisistratid Aqueduct p. 48

Fig. 7 Philo's Description of Ctesibius' Pump (Carra de Vaux) p. 83

Fig. 8 Philo's Description of the Bellows Pump (Carra de Vaux) p. 85

Fig. 9 Hero, *Pneum.* 23 (Woodcroft) p. 89

Fig. 10 Aristotle's Geometry of Memory (*Mem.* 452b13-23) p. 168

Fig. 11 Aristotle's Rainbow (*Mete.* 375b19-29) p. 179

Fig. 12 [Eucl.] *Opt.* prop. 1, B p. 194

Fig. 13 [Eucl.] *Opt*. prop. 2, B p. 195

Fig. 14 [Eucl.] *Opt.* prop. 54, B p. 198

Fig. 15 Aristarchus, *De mag*. *sol*. *et lun*. prop. 2 p. 205

Fig. 16 [Eucl.] *Opt.* prop. 9, B p. 211

Fig. 17 [Eucl.] *Opt.* prop. 35, B p. 214

Fig. 18 [Eucl.] *Opt*. prop. 25, B p. 215

Fig. 19 [Eucl.] *Opt.* prop. 35, reconstructed step one p. 217

Fig. 20 [Eucl.] *Opt.* prop. 35, reconstructed step two p. 217

Fig. 21 Ptolemy's Account of *Diplopia* (*Opt.* 2.33) p. 233

Fig. 22 Ptolemy's *Axis Communis* (*Opt.* 3.35) p. 235

Fig. 23 Ptolemy's Bronze Plaque (*Opt.* 3.8-9) p. 238

Fig. 24 Ptolemy's Eye (*Opt.* 4.4) p. 242

Fig. 25 Galen's Optic Chiasma (Version A) p. 257

Fig. 26 Galen's Optic Chiasma (Version B) p. 258

Fig. 27 Galen's Optics (*De usu part*. 10.12) p. 261

Fig. 28 Galen's Mechanism of Spatial Perception (*De usu part.* 10.12) p. 262

Fig. 29 A *Libella* p. 267

ACKNOWLEDGEMENTS

My deep thanks goes out to all those who have helped in the formation of these ideas and the construction of this document. My advisor, Katharina Volk, has been the most unfailingly kind, patient and helpful guide through this whole process, and I owe her immense thanks both for her direction and for her trust. My committee, Nancy Worman, Katja Vogt, Brooke Holmes and Matt Jones, have commented on this project along the way, and their thoughts have been extremely helpful and valuable. Earlier still, Gary McGonagill and Bethie Baxter helped propel me towards deep wonder at the ancient world. Great thanks and admiration goes to Caleb Dance, who has read through too many of my shaggy documents to count and without whom my time at Columbia would surely have been joyless and without music. Likewise, James and Zoe Tan have made getting a PhD an exercise in friendship from my first hours on campus, as have Charley McNamara, Joe Sheppard, Kate Meng Brassel, Mathias Hanses, Kate Stanley, Anne Diebel, Alicia DeSantis, Saskia Cornes and Leslie Barnes. Thanks to Julia Nordmann for getting me here. Calloway Scott and Kimberly Regler have been invaluable friends and wonderful readers, and I only hope that I can somehow repay them in kind. My appreciation also goes to the Mellon Interdisciplinary Fellows, who listened to a version of my project and offered wonderful advice, although special thanks to Bill McAllister, whose leadership of that group and resilience in loss this past year has been a powerful lesson in commitment to other human beings. Conversations with Steph Dick, Henry Cowles and William Deringer have sparked many ideas, even in the last months of writing my dissertation, and these three have made a Classicist feel welcome in the History of Science. Yet, I owe even greater thanks to Royden Kadyschuk, who has helped me in constructing the diagrams, and, more importantly, made the world a more fascinating place. Last, my deepest gratitude goes to my wife, Christina, who has shown patience beyond description in the last two years. She has been more than a partner, and I am still in awe of her generosity.

To my mother, father and brother.

To my wife.

Introduction: Technological Analogies and Physical Heuristics

Introduction: Theories and Things

What was the relationship between technology and scientific theories in antiquity? How did material artifacts affect the way that ancient natural philosophers thought about the world? Over the last sixty years, historians of science have paid far greater attention to the material circumstances of scientific discoveries, showing how the exigencies of experimentation (and to a far lesser extent field work) interact with and affect scientific knowledge.[1] Whether examining the physical limitations of technical apparatuses,[2] studying the networks of artisans producing scientific instruments[3] or analyzing the computational devices that both perform and embody mathematical calculations,[4] scholars have explored how abstract scientific ideas are both embedded within and sustained by material contexts. Yet, when trying to apply this model to ancient Greek and Roman sciences, a difficulty emerges: ancient scientific authors did not generally privilege experimentation as their prime means of discovery, nor did they commonly rely on material apparatuses as their main tools of legitimization.[5] Instead, they derived authority from other sources. In other words, they did not generally use technology to investigate the natural world—at least, not in the same way that modern scientists do.

[1] Far too many studies have investigated the material culture of science to be catalogued here. Two representative contributions include Shapin and Schaffer 1985, who investigate how the leaky air pump became the locus of two different scientific epistemologies, and Galison 1997, who examines the material culture of microphysics while focusing on shifting meanings of "experiment" and "experimenter."

[2] For instance, Burnet 2005 traces the insurmountable difficulty that lens makers faced when trying to produce perfectly parabolic lenses according to Descartes' mathematical instructions.

[3] Shapin 1989; P. Smith 2004.

[4] Dick 2014.

[5] A main exception would be astronomy, which employed many precise measuring tools.

How then does one examine the material and technological context of a science that (by and large) lacks laboratories?

A second difficulty compounds this primary obstacle. Despite their manifold intellectual advances in law, culture, science and philosophy, neither the Greeks nor the Romans are traditionally assumed to have produced an industrial revolution. They had no cars. They had no trains. They had no Spinning Jennies. After all, it is the absence of these technologies that provides one of the key criteria by which we determine them to be ancient. Scholars have proposed many theories to excuse this relative lack of material innovation—or, in other words, to assess what this "blockage" was all about.[6] The basic assumption that any such impediment existed has lost much of its currency in recent scholarship.[7] In fact, growing scholarly attention has emphasized that there actually were

[6] The term originally appeared in French as *blocage* in Schuhl 1947, who inaugurated this debate (cf. Hall 1983). Schuhl proposed a Marxist argument, claiming that innovation was hindered by the presence of slavery, which would have provided ample cheap labour, thus eliminating some of the economic incentive for increasing the means of production through automation; cf. Finley 1965; Meißner 1999: 19-20. Despite the attractiveness of such an economic causal story, it does not harmonize well with the fact that slavery was in its heyday from the third to second century BCE, precisely when the invention of new technology flourished in Alexandria; cf. M. Lewis 2000b. We might also point to historical comparanda and note that many technological innovations have been made during periods in which slavery has been practiced—including in modernity. The second most persistently cited cause of blockage is the aristocratic disdain for the "banausic" arts, which supposedly stunted technological growth. This argument derives largely from a few select comments: Plato disparaging the mechanical and banausic crafts (*Rep.* 495c8-d4, 522b2-5, 590c1-6), Aristotle stating that the banausic technicians are worse than slaves (*Pol.* 1260a37-b3, 1264b14-16) and Plutarch claiming that Archimedes did not write a treatise on his inventions because he thought that the mechanical arts were vulgar (*Marc.* 17.3-4); cf. Finley 1965: 33. It is this argument that Cuomo 2007: 4-6, 31-34 calls the "more insidious" of the two because of its prevalence and persistence. Indeed, however tidy these cultural attitudes may seem as motivating forces, they can only have limited explanatory power, since we should not assume that a few passages found in a select group of texts, written by an elite group of authors, represent an attitude shared by all segments of society—especially when these authors themselves are not entirely consistent on the matter. Certainly, significant people could have disdained those who worked with their hands, but large portions of ancient societies actually valued craftsmen—not least the craftsmen themselves. This makes the complete and total dampening effect of elitism hard to accept; cf. Cuomo 2007: 77-102.

[7] The idea takes for granted that improvement and progress are natural and inevitable for technology, as though the industrial revolution that happened in post-Enlightenment Europe were simply the logical extension of human nature and not a particular response to a certain set of economic, social and material conditions. It is possible that the Greeks and Romans may have actually invented what they needed to

a great number of innovations in the ancient world, so the very idea that neither the Greeks nor the Romans produced significant new technologies is false.[8] They may not have had cars, but they had sanitation and civil infrastructure, metallurgy and glassblowing, surgical tools and geared astronomical calendars.

Acknowledging the complexity of these devices can help us appreciate the considerable accomplishments of ancient technicians and allow us to understand the material circumstances of the Greco-Roman world more broadly. That being said, these developments cannot quite match the massive explosion of mechanisms that has occurred since the Enlightenment, and thus, referencing aqueducts, *automata* and the Antikythera mechanism may fail to satisfy a modern citizen of the 21st century who experiences a major technological revolution seemingly every year or two. Even if we give ancient developments the attention that they deserve, it is evident that neither the Greeks nor the Romans maintained precisely the same relationship to invention and production as we do. Therefore, when looking to understand the relationship between science and technology in antiquity, we cannot simply look to how the ancients produced ever better inventions, especially when a third problem then amplifies the second: while some astronomical devices relied on high levels of mathematical sophistication, most technological implements in antiquity did not require a great deal of specifically *scientific* wisdom.[9] For

invent; cf. Green 1994; Cuomo 2007: 3-6. For other arguments against assuming that any such blockage existed, see Balansard 1997: 16; Greene 2000, 2009; Wilson 2002.

[8] For various accounts of ancient technology, see Diels 1924; Neuburger 1930; Drachmann 1932; Forbes 1955-1964, 9 vols.; Moritz 1958; Price 1974; Hodge 1992. For the most recent accounts, see Wikander 2000; Humphrey 2006; Oleson 2008; Cech 2012. For a discussion of social attitudes towards technology, see Cuomo 2007.

[9] The most impressive piece of ancient technology is the Antikythera mechanism mentioned above. This had precise and carefully crafted gears that harmonized multiple calendars and astronomical cycles into a single computational device. Price 1974 provides an detailed examination of the mechanism, but Freeth, *et*

instance, even though constructing ships, catapults and aqueducts may have required a high degree of technical expertise, ancient technicians do not seem to have employed Aristotelian, Atomistic or Stoic physics while doing so.

Certainly, craftspeople must have had *some* theory about the behaviour of the materials with which they were working (e.g., wood floats and sinews have tensile strength), and they would have gained considerable knowledge about the natural world as a result of their experience. Nevertheless, it is unclear both to what degree their insights were supported by abstract scientific theories and to what degree their insights in turn informed (literary) scientists. A question then remains: how do you root abstract theories in their material contexts, when science was neither wholly dependent on technological implements, nor were technologies generally derived from scientific ideas? Despite the fact that these two subjects appear so intimately and intrinsically wedded to each other in the modern period, did 'science and technology' actually belong together as a unit in antiquity? Or, as Finley argues, was there "a clear, almost total, divorce between science and practice"?[10]

In short, my answer is no. Rather, I will argue that understanding technology is crucial to understanding scientific theory-formation in antiquity. Technologies provided material heuristics with which to conceptualize the natural world. In fact, ancient theorists often incorporated technological devices into their conceptual models, adopting tools and implements into their explanations of physical entities. Accordingly, I will illustrate how even if ancient theorists did not often apply technology directly to the

---

al. 2006 have updated his findings. In contrast to this level of precision, some portable sundials used approximations, while others still were merely decorative; cf. M.T.Wright 2000.

[10] Finley 1965: 32.

interrogation of nature, the tools around them nevertheless structured many of their ideas about the physical world.[11]

To be sure, for many years, psychologists and cognitive scientists have been assigning this type of analogical thinking a large role in how we conceptualize and comprehend phenomena. Rather than seeing analogies as mere teaching aides, researchers have argued that comparisons help make conceptual bridges between seemingly disparate fields, while also providing the very mechanism that allows us to categorize objects in the first place. Most recently, Hofstadter and Sander have gone so far as to claim that analogies are "the fuel and fire of thinking," or, in stronger terms, "thought's core."[12] They apply their observations to cognition in general, but spend time examining how even modern physicists use analogies to construct and conceptualize their theories. In this, they participate in a well-established tradition, since over the last fifty years, science studies has continued to show that the process of theory-formation is far less idealized than any positivist model might suggest; instead, it relies on a number of competing authorities, obligations and prejudices, while also incorporating such cognitive

---

[11] Another common approach in addressing the relationship between science and technology in antiquity is to examine ancient mechanical treatises to see whether technical authors incorporate philosophical ideas into their texts. For instance, commentators scan Hero's *Pneumatica* for traces of philosophical debates about the void (cf. Diels 1893; Wehrli 1850; Gottschalk 1964a; Fraser 1972, v. 1: 427-428; Lehoux 1999; Berryman 1997, 2009: 197-200), or analyze his *Belopoeica* to see how he positions mechanics as a discipline *vis-à-vis* philosophy (cf. Cuomo 2002. See also Schiefsy 2008, who examines the physical implications of Hero's *Mechanica*, but deals with the text as representative of actual practice). These studies have all provided valuable insights into the interaction between technicians and natural scientists, but shed light largely on the discourse of technology and philosophy. In contrast, I will focus more closely on material objects themselves.

[12] Hofstadter and Sander 2013: 3, 18. Many other works have focused on the importance of analogies in cognition, notably the seminal discussions of Black 1962; Ricoeur 1978 and Lakoff and Johnson 1980. For various discussions concerning the use of analogies in science in particular, see the early contributions of Oppenheimer 1956, Hesse 1966; Kuhn 1979; Gentner 1982, Gentner and Clement 1988 and Gentner and Jeziorski 1989. For a discussion about metaphors in ancient science, see Pender 2003. I am particularly endebted to Black's "interactive" view of metaphor, which discusses how metaphors and analogies can organize our conceptions (see esp. Black 1962, ch. 4), and Riceour's emphasis on the predicative force of analogies.

tools as analogies and comparisons.

Analogical thinking played a particularly strong role in theory-formation in the ancient world. As Lloyd has illustrated, comparison acted as one of the main tools with which Greek and Latin theorists constructed explanations.[13] Although far from exclusively so, these likenesses often invoke technological implements. Berryman and Schiefsky have drawn attention to this fact, pointing out numerous instances where ancient authors utilize technologies as heuristic devices.[14] Nevertheless, their work focuses primarily on explicit textual references, noting the passages in which theorists draw upon implements by name. While building upon their work, I am proposing that pairing an investigation of technological analogies with a closer study of actual physical tools can allow us to assess both 1) how broadly material technologies shaped physical assumptions and 2) when technological heuristics are active, even if they are not being mentioned explicitly. By recognizing how technologies inform ideas about natural behaviours, we can appreciate the degree to which scientific theories *reflect* their technological environments, even if they are not *producing* them. We can see how abstract ideas relate to material objects at work in the world—or, in other words, we can observe how *thought* relates to *things*.

Paying attention to physical devices themselves can also highlight a critical chronological aspect: technologies in antiquity developed over time. However modest some of these improvements may seem to us, even small material changes can alter scientific beliefs. Thus, by tracking how technologies shifted and improved, while

[13] Lloyd 1966.

[14] Berryman 2009; Schiefsky 2007; cf. Roby 2010, who discusses how Vitruvius in particular uses technological devices as heuristic tools.

observing how scientific ideas transformed in tandem with them, we can see how natural philosophers incorporated material advances into their theories. We can thereby discern how technologies can shape our basic assumptions about natural phenomena and the forces active in world.

I should make two key clarifications. First, I do not mean to imply that the ancients simply derived new observations or abstract *principles* from technological artifacts, as if material tools functioned solely as access points to the physical behaviours of nature. Without a doubt, interacting with implements would have revealed a great deal about the world, whether through weaving cloth, bending wood or firing clay. Nevertheless, even when theorists claim to make arguments based on abstract principles, these principles are often embodied in concrete technological devices, and the latter are crucial to theory-formation. In other words, technological implements do not merely supply information; they act as cognitive tools. As a result, particular material features of ancient devices find their way into physical theories, as theorists think with the specific devices in front of them, not some abstraction thereof. In other words, ancient theorists often conceptualized the world both *through* and in some cases *as* their contemporary technologies.

Second, I am not proposing some version of technological determinism, whereby scientific theories are either wholly dependent on or dictated by contemporary technologies. Material tools supply only one factor in the overlapping matrix of goals, observations and arguments that concern theory-formation. Moreover, considerable flexibility can exist within a single explanatory framework (people living in the same time period disagree about some basic physical principles after all), and even the same theorist can deploy a single technological analogy in different ways at different times. Thus, my approach to understanding the relationship between science and technology in antiquity will be to examine the localized role that technological artifacts play in enabling assumptions and arguments within scientific explanations. By paying close attention to how authors use these physical implements to construct theories, we can recognize the significant role of material culture in domains of thinking that are often considered abstract. We can understand how technology helps construct and maintain conceptual worlds. I will therefore examine the history of technology as a chronology of cognitive tools.

0.1 Analogies and Heuristics

In order to elucidate what I mean, I should define a few of my terms, starting with 'analogy' and 'heuristic.' By 'analogy' I mean the whole category of positive comparisons, including one and two term comparisons (a:b or a:b::y:x), similes (the longer, more figurative version of an analogy) and metaphors.[15] Although they differ formally, they all function conceptually in a comparable way. The larger argumentative structure that they help construct I call simply a 'heuristic.' This is a cognitive framework that activates certain ideas (and not others) and legitimates certain arguments (and not others). In other words, a heuristic is a conceptual apparatus that makes corollary claims comprehensible.[16] It is a set of interrelated assumptions that cohere.[17] Sometime these

[15] Although comparison can refer to both positive and negative juxtaposition (i.e. both comparing and contrasting), I am using the term to denote only the positive type.

[16] Cf. Black 1962: 44-45 for similar comments about his "interactive" theory of metaphors. We could also say that by this defintion the concept of a heuristic is itself a potential heuristic.

heuristics are made explicit by means of a comparison, while at other times, they are active even without the thinker necessarily being aware of it.

Let us consider a modern example. Imagine we are trying to explain (or understand) how brains work. We could attempt to do so—as many do—by comparing the brain with a computer. The basic comparison would be: 'the brain *functions like* a computer,' or more generically 'the brain *is like* a computer' (i.e. B:C). This insight can be employed in an analogy that is adopted for a localized argument or a single purpose, such as to explain how a brain calculates an answer like a computer calculates an answer (i.e. B:a::C:a), or to illustrate how a brain completes a cognitive task like a computer performs a function (B:t::C:f). At the same time, these comparisons and analogies also establish larger conceptual heuristics that potentially activate certain corollary arguments. In this case, the broader heuristic 'computer' or 'computer-like' would allow us to interpret multiple features of the brain, potentially including its behaviour, functional mechanisms, physical composition and use (e.g., the brain 'processes information' and 'stores memory,' or 'the synapses are on/off switches' and 'the brain works on electrical impulses'). Heuristics can reinterpret both physical and functional features of the target field of explanation. They grant meaning to parts. Yet, more than simply accounting for visible observations, these heuristics *predicate* features as well. In other words, these conceptual tools do not merely frame or interpret already-observed characteristics, but suggest and imply new ones. These can be functional (e.g., 'the brain processes and

[17] Heuristics can be established by means of analogy, but need not be. For instance, an analogical heuristic would be 'eyes see by functioning like cameras.' This would figure the eye's lens as a (camera) lens, the iris as an aperture and the retina as photosensitive film paper, thereby enabling a whole series of corollary claims that could potentially interpret other features of the eye. An example of non-analogical heuristic would be 'water boils when heat excites the atoms, which ricochet off each other and escape the water's surface.' This explanation involves a whole series of assumptions about atoms being solid, solid objects transferring motion to one another, heat supplying excitation, etc., although no comparison to a particular secondary device is made.

stores information in binary or some comparable code'), but are often physiological (e.g., the brain must have some as-of-yet-unseen physical structure that allows for information to be stored and processed in this binary language). In the context of modern science, these new features often form predictive claims that can potentially be tested (although not always),[18] and they thus shape both what experimenters are looking for and how they interpret what they find. In ancient science, however, these predicated structures often fall below the threshold of observation and must be assumed on the strength of the heuristic and its explanatory potential. What is perhaps more surprising, as I will illustrate in the coming chapters, heuristics often predicate features that directly contradict observable evidence—but are accepted nevertheless. In these moments, technologies have often come to *stand in* for the phenomenon under question, operating as metonyms rather than illuminating comparanda.

In part, what provides heuristics with such conceptual strength is the fact that they occlude certain information so that not every potential variable needs to be taken into account. While this is productive when making calculations or decisions, it comes with certain risks when forming theories.[19] Heuristics direct our attention to certain features of

---

[18] See Hesse's 1966 concept of a "neutral analogy," which she thinks enables testable predictions.

[19] Based on H. Simon 1956 and his work on "bounded rationality," Gigerenzer and Selten 2001 have used the concept of a "heuristic" to model a "naturalized rationality." They argue that "fast and frugal heuristics" more closely model the way that humans think than previous models based on computational optimization. They incorporate artificial intelligence into their discussion to help illustrate these ideas. Imagine trying to program a robot to catch a pop fly in baseball. One way to accomplish this would be to have the robot observe the trajectory of the ball as it leaves contact with the bat, the ball's velocity and spin, wind speed, air pressure, humidity and any other factors that might affect the flight pattern, and then, incorporating all these necessary variables, calculate the spot on which the ball will land. After it makes this calculation, the robot would start running. Even high-powered processing machines will fail to process all the required information before the ball lands. Instead, researchers have had more success with a different approach, one that looks to human baseball players to see how they catch a pop fly. First, fielders start off running in the general direction suggested by the trajectory, and then they lock their eyes on the ball. At that point, they attempt to keep that visual angle constant. If the ball always rests in the visual field at a constant angle, the ball and the player will always collide, regardless of where it lands. As this example shows, heuristics are

a phenomenon (and not others), excluding potentially troublesome information or irrelevant details. I call this implicit act of selection ‘cognitive focus.’ I choose ‘cognitive focus’ rather than ‘cognitive frame,’ since the aspects of the phenomenon around the boundaries are neither completely invisible, nor cut off entirely; they are simply blurry and demand little regard relative to the points on which our attention has been trained. These marginalized features can be made active again simply by readjusting our focus. Using a comparison to create a heuristic is thus both a creative and destructive act, producing new and potentially significant links, while excluding or at least marginalizing other possibilities. It directs attention to a small number of details, ignoring other aspects of the phenomenon, both physical and functional. For instance, to return to the computer heuristic, brains no longer ‘sense,’ ‘feel’ or ‘intuit,’ but only process and calculate. The heuristic will also suggest which physical features will be most meaningful, even when theorists are no longer employing the computer heuristic explicitly (or consciously). For example, experimenters may assume that the electric impulses of the brain are its operative feature, interpreting neurotransmitters as vehicles of electrical impulses. Other features, such as heat and oxygen (both of which can be seen in scans) take a supporting or derivative role.

As this last example shows, these heuristics can be extremely useful and can function as powerful tools to understand nature. Part of this potential comes from the fact that when trying to explain how some natural processes or body parts work, we tend to gravitate towards technologies used to complete similar tasks in the world. I call the conceptual power that these technologies exert ‘cognitive attraction.’ For instance, when

---

successful because they disregard certain information. They streamline calculations by occluding certain details. I am suggesting something similar happens not only in decision-making, but also in theory-formation and that what is occluded often depends on the technologies surrounding the theorist.

trying to explain memory, we will (generally) reach for technologies such as card catalogues, rolodexes, storage spaces, files, pictures, movies and (now) computer memory. Not only does this intuitive attraction set up potentially fruitful comparisons, it helps us avoid moving through all possible answers on the way to forming a causal explanation. Analogical heuristic are thus an incredibly useful way to attempt explanation, but staying attentive to their features will help reveal the interdependency of technological apparatuses and (scientific) conceptualizations of the world.

0.2 Science, Technology and τέχναι

In order to discuss how the concepts just discussed can help explicate the relationship of 'science' and 'technology' in antiquity, I should outline what I mean by both terms. In the case of the former, the boundaries are less consequential, since 'science' is not an ancient category, and imposing our definition on Greek and Roman practitioners would certainly be anachronistic. Nevertheless, many authors did construct models to explain the world around them and dealt with subjects now considered to be scientific disciplines. Thus, by 'ancient science' I simply mean those knowledge practices oriented towards providing explanations of physical phenomena by means of physical causes.[20] Some examples would include natural philosophy, astronomy, meteorology, biology and medicine, but one could also include astrology or alchemy. Of course, this is insufficient as a prescriptive definition, since a poet who claims that all diseases are sent by divinities is still producing a causal explanation, and authors can contest what

[20] I follow a similar approach to that of Keyser and Irby-Massie 2008, who include poets, astrologers and philosophers in their encyclopedia of ancient science.

constitutes a 'physical cause' in the first place.[21] Moreover, some historical actors engaging in what we would consider scientific practices rejected causal explanations entirely. For instance, the Hellenistic Empiricist physicians denied that it was possible to find the 'hidden causes' [*abditae causae*] in the body, yet still practiced medicine alongside other schools.[22] Ultimately, however, I am not interested in making strict distinctions between what does and does not constitute science in antiquity, since knowledge-claims were negotiated at different times by different historical actors, and attributing an honorific category to some of these actors at the expense of others would make an evaluative assertion that I would like to avoid to as great a degree as possible.[23] Instead, I will follow Lloyd's suggestion that "There is every reason in fact, for us to be as pluralist in *our* approaches as the ancient Greek theorists were in *their* views of their own inquiries."[24] Although scholars should be careful to avoid presuming that ancient scientists privileged, valued or even studied the same things that modern scientists do—or that they did it in the same way, for the same ends—[25] we can still investigate how ancient authors explained and conceptualized the physical world *qua* physical within a broad scientific tradition, without excluding *a priori* any relevant contributions.

---

[21] For instance, ancient theorists can consider natural attractive forces, cosmic tension and immanent rationality all to be physical causes.

[22] See Cels. *Med.* 1, *proem.* 27-39.

[23] I say this while acknowledging that accepting a broad definition of what qualifies as a 'science' in antiquity is itself an evaluative claim.

[24] Lloyd 1992: 574. We should also acknowledge that modern sciences themselves lack total cohesion: theoretical physics, observational biology and organic chemistry share neither subject matter nor a unified method, while disciplines such as psychology, psychiatry and the social sciences are even more contested; cf. Rihll 2002. For instance, Keller 2002 illustrates that even within the biological sciences themselves, different "epistemological cultures" accept different types of argumentation as sufficient explanations of life.

[25] Cf. Irby-Massie and Keyser: 2002, esp. 1-17; Rihll 2002.

Far more important for my purposes, however, is to outline what I mean by 'technology.' To begin with, it is tempting to base our understanding of the concept in antiquity on the Greek term τέχνη, which supplies the root for 'technology.' The word generally indicates 'expertise,' 'art' or even 'science.' Potential examples include rhetoric, poetry, weaving, prophecy and haruspicy, as well as more traditionally scientific subjects, such as medicine, metallurgy, mathematics and astronomy.[26] As Cuomo has shown, however, the boundaries of what did and did not constitute a τέχνη were hotly contested in antiquity and hinged on epistemological, economical and political concerns. To know a τέχνη was to possess expertise and thus to claim a certain type of power, whether to build a ship, speak persuasively or heal the sick.[27] Thus, because of its wide range of meanings, we cannot use τέχνη alone to guide our understanding of technology in antiquity, especially since in all these cases τέχνη denotes a knowledge *practice*, not the material result of that practice, and the latter is where my interest lies. More importantly, however, it is somewhat problematic to ask 'how did ancient science relate to τέχνη?' since the two categories in many cases mean the same thing.

---

[26] Scholars often juxtapose the term τέχνη with ἐπιστήμη and emphasize that τέχνη is knowing-*how*, while ἐπιστήμη is knowing-*that*. In other words, τέχνη is a science involving production and expertise, while ἐπιστήμη is a science derived from first principles (for Plato and Aristotle's formal accounts of τέχνη, which emphasize rationality and teachability, see Mitcham 1979: 172-183; Balansard 1997, 2001). There are multiple problems with these definitions, not least of which is that they are derived not from a complete survey of the terms, but from comments made by Plato and Aristotle, neither of whom applies these categories consistently; cf. Balansard 1997, esp. 116-130). Moreover, Cuomo 2007: 9 points out that τέχνη can be used as a synonym for σοφία or δύναμις, as well as for ἐπιστήμη itself. In any case, even if these two authors did utilize rigourous category-distinctions, these ideas would still only constitute the opinion of two philosophers and not necessarily represent views shared by a wider majority of Greeks, let alone across the thousand-odd years that span antiquity. For a more general dicussion of the relationship of nature and technology in ancient science, see von Staden 2007.

[27] Cf. Cuomo 2007: 1-40, esp. 29-34. She notes that the Hippocratic author of *On Techne* writes an entire treatise devoted to the contested claim of what does and does not constitute a τέχνη. She offers a full examination of the term.

In signifying a type of knowledge, τέχνη means something similar to what 'technology' denoted when it was first introduced into the English language in the 17th century, although at that point, the term referred solely to treatises concerning mechanics.[28] The semantic range soon expanded to encompass not only the actual knowledge of how to produce something, but also the organizational infrastructure of both manufacture and use. In other words, 'technology' could refer to either systems of production or implementation.[29] While these older uses are still in circulation, it is much more common in current English for "technology" to refer to a material product or tool. In the last century, these technologies were primarily associated with mechanical devices, but at present, the term functions primarily as a catchall to refer to any digital implement (i.e. people will be far more likely to consider a smart phone a "technology" than they will a lever; we can also consider the "tech sector"). For our purposes, however, I wish to consider something more modest: the every-day tools and manufactured objects found in antiquity. How do these types of technology relate to science? How do the material implements that we use in our daily lives affect our assumptions about the mechanisms of nature? Thus, I am not asking only how craft-knowledge informs scientific knowledge, but how actual *artifacts* relate to abstract philosophical theories.[30]

---

[28] Schatzberg 2006 traces the English use of the term 'technology,' which emerged in the 17th century and referred to treatises on the mechanical arts up through the 19th century (as evinced by the -logos suffix). It was only in the 20th century that the term started primarily to refer to the artifacts of production themselves; cf. Mitcham 1979: 183-188; Marx 2010; Roby 2010: 8-9.

[29] Critical theorists have adopted the term to refer to the techniques and systems used to implement any ideology, whether "technologies of the self" (cf. Foucault 1988), "technologies of gender" (De Lauritis 1987) or "technologies of race" (Sheth 2009, esp. 21-39). For an examination of technologies as social systems, see Bijker, Hughes and Pinch 1987.

[30] Let us consider a tennis racquet. Today, 'technology' can denote: 1) the information contained in an instruction manual describing how to make a racquet (production knowledge); 2) the structure of the assembly line or workshop that produces it (production infrastructure); 3) the rules of tennis and the physical court, with its white lines and net (utilization infrastructure); and 4) the tennis racquet itself

There are a few scholars who have shed some light on this question. For instance, many historians of science have explored the role that mechanical knowledge played in the rise of materialist natural philosophies in the 17^{th} century, when the reintroduction of the mechanical treatises of pseudo-Aristotle, Archimedes, Vitruvius and Hero led to a renewed interest in *automata*, clocks and physical mechanics. These in turn led to the corpuscular and 'clock-like' ideas of nature found in Descartes and Boyle.[31] In recent work, Berryman and Schiefsky have sought to overturn this chronological narrative by looking at how the mechanized devices of antiquity provided similar heuristics for ancient authors, who used them in their accounts of nature.[32] In this, they join many other historians of science, who seem to presume that some threshold exists above which implements are sufficiently technological so as to be philosophically consequential, but below which they are more or less unimportant. Price makes this tendency explicit, insofar as he divides technologies into categories of "Low" and "High" and assigns them scientific significance accordingly:

> [Low technologies are] the sort of crafts that all men in all cultures have used in all ages for building houses and roads and water supply, making clothes and pots, growing and cooking food, waging war, etc. [High technologies, in contrast, are] those specially sophisticated crafts and manufactures that are in some ways intimately connected with the sciences, drawing on them for theories, giving to them the instruments and

(produced artifact). Each simple, material artifact bears traces of the multiple systems of production and implementation that brought it into existence, so that behind every technology (4) lies multiple technologies (1-3). For my present purposes, however, I am not chiefly interested in technologies as totalizing systems—whether of production, signification, operation or domination—but as far more localized, material tools. I am primarily interested in the racquet.

[31] Laird and Roux 2008: 1-11 presents this standard view. For a discussion of the mechanical metaphors in Descartes' natural philosophy in particular, see Des Chenes 2001.

[32] See Berryman 2009; Schiefsky 2007; cf. Schiefsky 2008, in which he proposes a two-way interaction between "practical" and "theoretical" mechanics. Yet, because his comments concern how the *idealized* machines of Hero's *Mechanica* interact with mathematical accounts, to my mind, his valuable study primarily concerns two different forms of theoretical mechanics.

> the techniques that enable men to observe and experiment and increase both knowledge and technical competence (Price 1974: 52).[33]

Price places considerable weight on clocks and considers their intricate moving parts to be crucial to the formation of modern science in the West—and to be sure, the gearwork of the Antikythera mechanism remains extremely impressive, a testiment to the technical knowledge and skill of ancient artisans.[34] Yet, despite Price's assumptions, while the technologies used for building houses, roads, water supply, cooking, etc. may have existed for thousands of years, they too have had their own history and have changed over time. They may not be mechanical, but they are still technologies and are still the products of a manufacturing process. Most importantly, they still have a deep impact on assumptions about how nature functions. In fact, even modest developments in such basic materials as glass, pipes and mirrors can have a profound influence on the way ancient authors understand the physical world, providing a new conceptual framework around which explanations can be built. Thus, in examining how 'technology' related to science in antiquity, I am proposing to expand the definition of technology—even beyond what constituted a τέχνη—to include the non-mechanistic devices that made up the majority of ancient implements.

0.3 Divine Demiurge and Nature as a Technician

I have suggested that the category of τέχνη is too broad to determine what we can consider an ancient technology for our purposes, but it is also too narrow, since τέχνη refers to a knowledge practice, not the material product of craft-knowledge, which can instead be referred to as a 'tool' [ὄργανον], 'device' [μηχανή] or simply given its own

[33] Cf. Lewis 2001: 9.
[34] Cf. n. 9.

name (e.g., soap, cloth, amphora, etc.).[35] Yet, despite the fact that I am not rooting my investigation solely in the vocabulary of τέχνη, I am still interested in how those seeking to explain natural phenomena deploy this concept in a particular way, namely, in the image of nature as 'technical' [τεχνική]. In this particular formulation, authors are not considering the relevant τέχνη to be poetry, prophesy or rhetoric, but some type of productive art or craft. This fact enables us to examine how a certain kind of material technology infiltrates scientific conceptions.

The image of a divine craftsman appears already in Hesiod, who discusses the generation of the gods as the product of sexual union, but describes how Hephaestus—the paradigmatic artisan god—constructs Pandora and the female race after her by means of his craft.[36] Empedocles utilizes the image in a similar way, describing a somewhat anthropomorphized Nature [φύσις] who constructs the eye like a lamp,[37] manufactures the bones as though mixing glue[38] and molds human complexions with her hands.[39] Similarly, Xenophon refers to god as an artisan or "demiurge" [δημιουργός], who constructs the body as a technical artifact [τέχνημα] and crafts our eyelids as doors, our eyelashes as strainers and our eyebrows as battlements.[40] A demiurge can be any type of artisan or technician (literally one who 'works for the people'), including handicraftsmen,

[35] The word μηχανή can refer to a material device, such as the crane used to lift characters aloft on the dramatic stage, or to an immaterial device, such as a 'strategem' or 'trick' used to fool someone; cf. Schiefsky 2007: 77-82.

[36] Hes. *WD* 59-73, 106-201; *Theog.* 571-593. Solmsen 1968a discusses the transition between narratives of generation and creation in Greek theogonies; cf. Balansard 1997: 10-11. For the most recent account of ideas about divine creation in antiquity, see Sedley 2007, esp. 107-112.

[37] Emped. DK 31 B 86.

[38] Emped. DK 31 B 96.

[39] Emped. DK 31 B 75, ln. 2; B 95.

[40] Xenoph. *Mem.* 1.4.6.

workmen, sculptors, cooks, etc., but the emphasis lies on those who produce and create material products.

Perhaps the most extensive use of this idea comes from Plato in his *Timaeus*. Throughout this dialogue, he employs this metaphorical scheme as he describes the composition of the universe, referring to the creator god as the "father and the maker of the entire cosmos" [ποιητὴς καὶ πατὴρ τοῦ παντός], the "carpenter" [ὁ τεκταινόμενος] and the "good demiurge" [ὁ δημιουργὸς ἀγαθός].[41] Aristotle too adopts a similar position, although he makes the creative power more immanent, turning nature itself into the artisan rather than considering it the simple raw material available for a divinity to manipulate.[42] As he states in *De partibus animalium*:

> ὥσπερ γὰρ οἱ πλάττοντες ἐκ πηλοῦ ζῷον ἤ τινος ἄλλης ὑγρᾶς συστάσεως ὑφιστᾶσι τῶν στερεῶν τι σωμάτων, εἶθ᾽ οὕτω περιπλάττουσι, τὸν αὐτὸν τρόπον ἡ φύσις δεδημιούργηκεν ἐκ τῶν σαρκῶν τὸ ζῷον.
>
> Just as those sculpting an animal from clay or some other moist composition establish some hard body and then sculpt around it, in this same way nature has constructed animals from flesh (Arist. *Part. an.* 654b28-31).

Aristotle has very specific teleological goals in mind when presenting nature in this manner, stating in the *Physics* that just as a technician completes all of his individual actions with some larger goal in mind (e.g., producing a functioning house of a certain type), so too does nature construct the parts of animals with a similar goal in mind (i.e.

[41] Pl. *Tim.* 28c3-29a3; cf. 41a7, where the creator god calls himself a δημιουργός. This demiurge crafts all *immortal* things, while his offspring, our "superiors" [οἱ κρείττους], construct [δημιουργεῖν] all mortal, perishable things in turn; cf. Pl. *Tim.* 69b8-c8.

[42] Cf. Solmsen 1968a: 344.

producing a functioning animal of a certain type).[43] Within this general framework, Aristotle asserts many corollaries, namely, that "nature constructs nothing in vain" [ἡ φύσις οὐδὲν δημιουργεῖ μάτην],[44] builds things for a reason,[45] does nothing at random,[46] always seeks an end,[47] always seeks what is useful[48] and always does the best possible thing.[49]

The idea of a technical nature strongly influenced later authors, including the Stoics, who propose that all natural creative acts resulted from a "technical fire" [πῦρ τεχνικόν] running through all things.[50] Even more than the Stoics, though, it was Galen who fully adopted the idea of nature-as-technician [τεχνικὴ φύσις],[51] and he uses the premise to structure his work *De usu partium*, which outlines the form and function of each anatomical structure within the body, illustrating why even the smallest part could not be formed in any other way without impeding the function of the body as a whole. His texts contain numerous references to nature designing, building and constructing

---

[43] Arist. *Ph.* 199a9-20. Leunissen 2010 examines the teleological structure to Aristotle's biological explanations, but notes that there are actually two levels to this: primary teleology, which addresses the essential features of an animal, and secondary teleology, which addresses features that are not essential, but merely 'for the better.'

[44] Arist. *IA* 711a18; cf. *IA* 704b15; 708a9; 711a7 (this passage states somewhat tautologically "nature does nothing against nature" [ἡ δὲ φύσις οὐδὲν ποιεῖ παρὰ φύσιν]); *De an.* 432b21; 434a31; *Cael.* 271a33; 291b13-14; *Gen. an.* 739b19; 741b4-5; 744a36-38; *Resp.* 476a13; *Part. an.* 658a8; 661b24; 691b4-5; 694a15, 695b19-20; cf. Falcon 2007: 88, n. 4.

[45] Arist. *Gen. an.* 731a24.

[46] Arist. *Cael.* 290a31.

[47] Arist. *Gen. an.*715b15-16.

[48] Arist. *Hist. an.* 615a25-26.

[49] Arist. *Cael.* 288a2-3; *Ph.* 260a22-23; *Gen. corr.* 336b27-28; *De juv. et senec.* 469a27-28; *Part. an.* 658a23; 687a16-17; *IA* 704b15, 708a9-10.

[50] *SVF* 120; 171.9; 774.2; 1021.9; 1027.2; 1133.2; 1134.1; Aët. 1.7.33.

[51] Gal. *Nat. Fac.* K. 2.131.12.

bodies as an artisan would, carefully crafting each detail with a high degree of precision.[52]

It should not be surprising that when those who employ the larger structural metaphor of nature-as-craftsman attempt to explain and understand how particular natural phenomena work, they often draw on technical artifacts as conceptual tools. After all, if 'Nature' is a technician, then 'nature' can be composed of technologies. Yet, despite the fact that it was quite common in antiquity for natural philosophers to assume that nature possessed considerable technical skill (especially among those with certain teleological goals), calling nature 'technical' could have meant something quite different in fourth century BCE Athens—with its pots, bronze tools and cisterns—than it did in second century CE Rome—where large-scale aqueducts, elaborate water machines and extensive glassworks were commonplace. These different technological environments facilitated different conceptualizations of natural phenomena, especially for those theorists who were already looking towards craft knowledge as a heuristic to understand the world. To be clear, technological analogies are far from the only tool with which ancient scientific authors attempted to construct explanations, and multiple texts lack this type of argumentation altogether. Nevertheless, the tendency to reach for man-made implements to make natural phenomena comprehensible represents a cross-disciplinary technique, with examples found in each scientific discipline and all philosophical schools, regardless of authors' specific commitments towards teleology. This is not to argue that all theorists held the same relationship to technology, only that theorists with varying ontological and

[52] For references to nature 'crafting' [δημιουργεῖν] the body, see Gal. *Nat. fac.* K. 2.23.12; *De usu part.* 1.18 K. 3.64.14, *et passim.* Erasistratus of Ceos also refers to a τεχνικὴ φύσις (fr. 79, 80; cf. fr. 78, 81, 83, 103, 149 Garafalo); cf. [Hippocr.] *Epid.* 6.5.1. Even outside of this particular medico-philosophical tradition, Vitr. *De arch.* 9.1.2 displays a similar impulse, insofar as he casts the power of nature (with perhaps just a little self-promotion) as an architect [*naturalis potestas architectata*].

epistemological ideas all still often utilized technologies when conceptualizing the processes of nature.[53]

0.4 (Technological) Analogies as a Scientific Method

Perhaps the most frequent use of technological analogies occurs within the medical and biological traditions seeking to understand the physiology of the body.[54] Sometimes these analogies are extremely basic and refer to simple material practices, such as the widespread assumption that digestion is a form of cooking or 'concoction' [πέσσειν], whereby we digest food internally by means of the same technique that makes food digestible externally.[55] At other times, authors treat physiological organs as basic implements, presuming that the body utilizes tools [ὄργανα] in the same way as human practitioners do. For example, the Hippocratic author of *Ancient Medicine* explains that organs such as the bladder, the brain and the womb are shaped like medical 'cupping glasses' [αἱ σικύαι], which allows them to attract bodily humours.[56] In this way, he

---

[53] While nature-as-craft easily harmonizes with certain teleological claims, many non-teleological theorists still use technologies as analogic heuristics. For instance, Lucretius insists that the heavenly bodies were arranged "without any design" [*neque consilio*] or "keen discernment" [*sagaci mente*], and instead argues that they fell into place because of the random collision of atoms and the force of their own weight (*DRN* 5.416-431). Nevertheless, less than a hundred lines later, he describes the mechanism of their motion as potentially driven by celestial currents pushing them in a circle around their poles, "just as we see rivers rotate wheels and buckets" (*DRN* 5.516). That is, even after describing a non-purposive universe, Lucretius still uses a technological device—the water wheel—to conceptualize the mechanism of celestial rotation. To be fair, Lucretius writes his philosophical treatise in poetry, which is perhaps a medium more prone of these types of analogies, but we should not therefore ignore their explanatory force or scientific relevance; cf. Garani 2007, who examines the prevalence of analogies in the work of Empedocles and Lucretius.

[54] See especially the Hippocratic treatises *Nat. Puer.*, *Genit.* and *Vict.* 1-4.

[55] See Lloyd 1996: 83-103 for a fuller explication of this concept within Aristotelian biology; cf. Jouanna 1999: 314, 320. The verb πέσσειν can also refer to fruit ripening, which is seen as a type of concoction as well.

[56] [Hippocr.] *VM* 22; cf. Jouanna 1999: 317-322, who emphasizes the importance of analogies in Hippocratic explanations. These cupping glasses are of two types. The first kind functions by placing a piece of flaming lint underneath the cup, as it is pressed against the skin. The lint does not produce enough

presumes that the devices attracting humours *within* the body function in the same way as the devices attracting humours *from* the body. Similarly, Aristotle likens how we move our limbs to the way that wind-up puppets [τὰ αὐτόματα] use a small impetus to set limbs in motion, and he compares our sinews and bones to the puppet's cables and pegs. In other words, he suggests that the body moves in the same way as an automaton constructed to reproduce animal motion.[57]

A comparable instance occurs in the meteorological tradition, when Seneca explains hot springs by arguing that underground channels take water through subterranean fires, just like pipes in baths that are coiled around a furnace, and he points to the natural baths at Baiae as proof of his theory—that is, he uses an artificial bath to explain a natural phenomenon, only to then employ a natural instance of this phenomenon to support the application of his technological analogy.[58] Lastly, a similar moment takes place in the astrological account of Aratus, who compares the motion of the celestial spheres to an armillary sphere with its consecutive rings fastened to each

heat to burn someone, but enough to warm the inside air and create a vacuum, drawing the surface of the skin into the cup. The second type of cupping glass has a small pipe sticking out the top. This pipe can be sucked and then quickly sealed with wax, therby drawing flesh up into the cup in much the same way. Analogy with these devices is used to justify almost any physical phenomenon that involves attraction, be it the attraction of 'like for like,' magnetism, gravity, etc.; cf. Soranus, *Gyn.* 1.9.1 who uses them to describe the womb.

[57] Arist. *De motu an.* 701b2-9; cf. [Arist.] *Pr.* 4.23.879a16-18, which asks how erections work, suggesting that they might occur on the model of a lever and fulcrum: "because weight added in the space behind the testicles raises it (for the testicles are a fulcrum) and air fills the passageways" [διά τε τὸ βάρος ἐπιγίνεσθαι ἐν τῷ ὄπισθεν τῶν ὄρχεων αἴρεσθαι (ὑπομόχλιον γὰρ οἱ ὄρχεις γίνονται) καὶ διὰ τὸ πνεύματος πληροῦσθαι τοὺς πόρους].

[58] Sen. *NQ* 3.24.2-3. Seneca claims that Empedocles had the same theory, but baths of this nature did not exist in Empedocles' time (Ginouvès 1962 provides a thorough examination of Greek baths, but for the most recent studies, see the various contributions in the edited volume of Lucore and Trümper 2013). Moreover, Aristotle suggests that Empedocles held the earth to be like a body, not a bath; cf. Arist. *Mete.* 357a24-28. Seneca's meteorology abounds with technological analogies; cf. Williams 2012.

other.[59] Once again, this Greek theorist explains the motions of heavenly bodies with a piece of technology constructed precisely to embody those motions. These instances represent extreme examples of what could be considered a general cognitive habit, that is, to explain the process of nature with technologies used for similar ends. The fact that authors sometimes actually employ an artifact designed to *mimic* those natural behaviours provides what can be considered the apotheosis of this impulse.[60]

The examples that I have given draw from different texts, written for various audiences, with different goals in mind, including philosophical treatises, poetic accounts and medical manuals. We should therefore be careful not flatten out the multiform methodologies and varying epistemological commitments found in each discipline and each author—let alone in each text. Aristotle, for instance, exercises considerable care in delineating how closely his analogies align with the phenomena under question, employing these comparisons frequently, but judiciously, within the framework of larger philosophical arguments. In distinction, Empedocles explains certain phenomena by utilizing extended similes to technological artifacts (much in the same way that Homer illuminates human actions by poetic comparisons with animals in the natural world) and does not seem concerned with negotiating the boundaries between analogue and the target field of explanation. In this way, he encapsulates a strong version of a scientific tendency that I would like to explore, namely, something I call 'analogic drift.' This occurs when technological analogues control the parameters of explanation to such a degree that they become epistemologically dominant over the very phenomena that they

[59] Aratus, *Phaen.* 462-468.

[60] Cf. [Hippocr.] *Vict.* 1.11-12, which claims that humans unwittingly mimic τέχναι, although the passage appears to be referencing the medical arts, not material artifacts; cf. Schiefsky 2007: 71.

are invoked to explain. In other words, while authors often employ implements as *analogues* to explain natural processes, these implements sometimes end up standing in as *metonyms* for the physical world itself—or, to use the same terms as before, ancient scientists often think about natural processes both *through* and *as* certain technologies.

Explicit comparisons thus allow us to mark moments where technologies provide conceptual apparatuses. Yet, these moments can also help us assess where technological heuristics are active more broadly, even when they are not explicitly mentioned. In fact, authors may not even be aware that technologies are structuring their physical assumptions and may instead presume that the world simply 'works like that.' Thus, although I will draw on explicit comparisons to authorize and anchor my interpretations, I will use them to gain access to larger heuristic frames. Ultimately my interest lies in how technologies supply cognitive tools, and although analogy forms a large component of this, it is not the only way in which technologies perform this function within theory-formation. Thus, despite emphasizing analogical heuristics, my investigation extends beyond straightforward comparative models that employ *existing* material implements as conceptual tools to include two additional categories of technology: those that *represent* natural phenomena and those that *interrogate* natural phenomena.

For my purposes, diagrams operate as the prime example of the first category, insofar as the authors of applied mathematical texts use geometrical images to articulate and represent certain physical entites and behaviours. In this way, diagrammatic technology provides a powerful conceptual tool to model the world. Yet, I will argue that in functioning as a conceptual tool, diagrams end up producing very similar effects to the material implements incorporated in analogies—that is, diagrams too predicate certain physical features, while simultaneously taking a type of epistemological dominance over the target field of explanation. Moreover, it is often the visual, material features of diagrams that generate certain physical arguments. In other words, a diagram is a technology that also produces a physical heuristic. Thus, I include them as crucial components of understanding the relationship of technology and theory-formation in antiquity.

The third category of technologies comprises those few instances in antiquity where theorists interrogate physical behaviours and entities by constructing tools in the form of experimental apparatuses. While employing these devices implies a particular set of epistemological commitments (and as such these technologies are more rare), tools of this sort still produce consequences similar to the previous two categories, insofar as the apparatuses used to *investigate* physical behaviours often become incorporated into ideas about the operational mechanism under investigation. In other words, devices used to look at certain phenomena become models for how these phenomena function. In this way, experimental apparatuses too produce physical heuristics. Thus, while I examine how scientific implements affect theory-formation, I will not focus on what new information they reveal about the world by means of their experimental capacities, but how they furnish cognitive tools, thereby structuring ideas about the phenomenon at issue. With all these types of technology, I am interested in how particular material features find their way into abstract thought. While these devices were used for different ends, both practically and scientifically, they produce a common set of consequences for theory-formation.

0.5 Chapter Outline

In order to explore these broad concerns, I will focus my examinations on two main fields: 1) explanations of respiration and the vascular system and 2) theoretical accounts of vision. By dealing with multiple treatments of these two phenomena and examining how different technologies shape theoretical accounts over time, I can address how material environments facilitate physical assumptions. Moreover, by focusing on the specific features of implements in each period, I can emphasize how thinkers adopt their particular technologies, not simple abstractions, as cognitive tools. As a consequence, even small technological changes can produce larger conceptual shifts. To provide this diachronic perspective, my investigations move from Empedocles to Galen.

In the first chapter, I explore how Greek water-delivery systems of the fifth and fourth centuries BCE shaped ideas about blood delivery, and I show how such authors as Plato and Aristotle use multiple analogies to explain overlapping bodily systems—and in the process deploy alternating analogues that facilitate the proximate goals of their arguments. I thus address the *modal* use of technological heuristics to see how theorists can shift from one explanatory framework to another to make different claims *en route* to providing a larger picture of how a phenomenon works—even if these frameworks conflict. Technological heuristics can be utilized on a localized level to serve immediate goals and do not necessarily function as overarching, permanent windows into natural laws.

In the second chapter, I illustrate how the rise of pneumatic technology in the third century BCE led to a corresponding shift in medical thought. Whereas earlier thinkers understood blood-delivery on the model of flow, Erasistratus of Ceos pressurized the vessels of the body and modeled the heart on the newly invented force pump. In this way, he represents a prime example of someone who incorporates new technological advances into his theoretical account of nature. In the second half of the chapter, however, I discuss the medical theories of Asclepiades of Bithynia to counter any assumptions about technological determinism, demonstrating that the influence of technologies is not a linear progression of ever more sophisticated tools, but that older implements can produce just as great an effect on a cognitive environment as a new device. To this end, I introduce the concept of a cultural heuristic—a conceptual framework so commonly shared that it does not need to be explicitly mentioned in order to be active. Through this examination, I interrogate the degree to which our technological environments make us receptive to certain types of arguments and not others.

In the third chapter, I consider ancient theories of vision and examine how using different technological heuristics alters the operational definition of what is meant by 'sight.' I argue that by using different explanatory frames, ancient theorists changed not only the *types* of explanations offered, but also what the boundaries of the phenomenon under investigation actually constituted. I first explore how early Greek theorists utilized technologies such as the mirror and wax tablet to conceptualize the process of vision, analyzing how multiple competing analogues can affect the interpretation of a single phenomenon. I suggest that Anaxagoras and Aristotle make certain conclusions about the eye based on the specific reflective surfaces used in classical Greece. In this way, I show that theorists do not think with pure abstractions, but adopt their *particular* technologies with their *particular* material features as representative of how nature works *per se.*

In the fourth chapter, I expand the type of technology I am addressing to argue that diagrams operate in a similar way to analogical heuristics. I show how the material exigencies of ancient geometrical practices find their way into the physical assumptions of Aristotle and Euclid, and thus I argue that while diagrams *supposedly* represent mathematic abstractions of physical entities, suppositions about these entities are bound up with their physical representation in geometric space. Diagrams as a material technology thus operate like the other tools already examined.

In the fifth and final chapter, I turn to Ptolemy and Galen to address some of the few experimental apparatuses used in ancient optical science. On the one hand, these devices structure the experience of sight, dictating some of its essential features and providing insight into the functional mechanics of vision. On the other hand, I demonstrate how the physical features of these tools become incorporated into assumptions about the physiology of the eye itself. In other words, Ptolemy and Galen use their experimental apparatuses as technological heuristics to understand the operative features of the eye.

In all these chapters, I articulate the interplay of the physical and the abstract, the natural and the artificial, the observed and the constructed to see how technologies can influence and act as scientific theories. Moreover, by focusing on how theorists *use* individual technologies in their arguments, rather than simply collecting what they say about technology more generally, we can glimpse how scientific explanations are actively formed and supported. Moreover, pairing this investigation with an examination of actual material devices helps embed ancient science within its material context and pushes abstract thoughts closer to their technological surroundings.

CHAPTER ONE
THE VASCULAR SYSTEM AND WATER TECHNOLOGIES

1.0 Introduction: Technologies as Heuristics

Second century BCE medical encyclopedist Celsus names respiration and the distribution of blood as two of the paradigmatic "natural actions" [*actiones naturales*] (along with digestion, sleeping and waking), which rationalist physicians believe that they must know if they are going to treat illnesses of the body well.[61] Yet, he also mentions that authors disagree about how these physiological processes work. These hidden activities of the body need to be inferred from visible behaviours and gleaned from known anatomical features. As such, they represent prime examples of the unseen, opaque mechanisms just below the threshold of direct observation that theorists attempted to conceptualize and explain in antiquity. In this chapter, I will examine how authors used material technologies to decode this information. By tracing theories of respiration and blood-delivery within the philosophical and medical traditions, while paying close attention to the actual material analogues authors describe, I will show how particular Greek water technologies influenced contemporary theories of the lungs, heart and blood vessels from the fifth to the third century BCE. We can then see the degree to which the technological environments of these authors informed and provided their conceptual tools.[62]

[61] Cels. *Med.* 1, *proem.* 19.

[62] Blood circulation was not discovered until Harvey in the 17th century. By contrast, the ancients thought in the more generic terms of blood flow and distribution, where blood is actually consumed by the body, obviating the need for circulation; cf. Longrigg 1988: 479.

What is perhaps most surprising is that despite the wealth of new inventions during this period, no new physical principles were discovered.[63] Rather, well-known physical concepts such as mutual displacement and vacuum pressure were simply redeployed in new ways. This creativity led to the invention of many new mechanisms, including the force pump, the inverted siphon and the water organ. As a result, physical theories of the body also changed in ways that reflected these new devices. Thus, by tracking how new *technologies* influenced conceptualizations of respiration and the cardiovascular system, rather than simply new *principles*, we can see how ancient natural philosophers did not build their theories by thinking through abstract ideas alone—even those supplied to them by their technological environments. Instead, they often thought with individual technologies themselves. As a corollary to this argument, by placing cardiovascular theories in their historical and technological contexts, we can make better sense of certain anomalous aspects of ancient Greek physiological models.

1.1 Technological Analogies as Technological Metonyms

Before we turn to ancient theories of the vascular system and blood-delivery, it will first be useful to examine the earliest account of the respiratory system found within the philosophical-scientific tradition—that of Empedocles. As mentioned in the introduction, Empedocles uses technological analogies to explain several phenomena, but he does not employ them as mere teaching aids to communicate already well-formed physical theories. Instead, he structures many of his explanations on these implements, and accordingly, his comparisons do a great deal of conceptual work for his arguments.

[63] For a discussion of whether ancient natural philosophers understood the behaviour of water to be a set of natural 'principles,' especially in regards to different formulations of *horror vacui*, see Berryman 1997; Lehoux 1999.

In fact, sometimes he uses these analogies in direct contradiction with another part of his overarching theory, as if the persuasiveness of the comparison outweighs the potential dissonance with his general explanation. Insofar as he lets technologies stand in as metonyms for the phenomenon under investigation, he can serve as a starting template, albeit an extreme version, for the rest of my investigation.

To explain how we breathe in and out, Empedocles relies on an extended analogy between the body and the *clepsydra*, a rigid pottery vessel used to transport wine by a siphon mechanism. The *clepsydra* is a simple device, a vessel with perforations on its bottom (which allow liquid to enter its main cavity), and a spout on top (which can be plugged to prevent liquid from flowing back out) (fig. 1):[64]

Fig. 1 An image of a *clepsydra* device[65]

This device functions in the same way as a straw, when a child sticks one in a can of soda, places her finger over its top opening, traps a bit of liquid in the end and then transfers it to her mouth (or maybe drips it on her brother). However simple this tool may be, it had a substantial impact on ancient theorists, and authors in multiple disciplines

[64] See M. Lewis 2000a: 343-345 for a description of the *clepsydra*.

[65] All drawings and diagrams are my own unless otherwise indicated. Many thanks to Royden Kadyschuk for helping to construct them.

point to this technology to support various theories involving the power of air. For instance, Aristotle reports that Anaximenes, Anaxagoras and Democritus used the *clepsydra* to illustrate why the earth's breadth allowed it to remain stationary, suggesting that the earth traps air beneath it, which prevents it from falling.[66] Empedocles, however, used the device to explain respiration, and Aristotle preserves his account in full:

> ὧδε δ' ἀναπνεῖ πάντα καὶ ἐκπνεῖ· πᾶσι λίφαιμοι
> σαρκῶν σύριγγες πύματον κατὰ σῶμα τέτανται,
> καί σφιν ἐπὶ στομίοις πυκιναῖς τέτρηνται ἄλοξιν
> ῥινῶν ἔσχατα τέρθρα διαμπερές, ὥστε φόνον μέν
> κεύθειν, αἰθέρι δ' εὐπορίην διόδοισι τετμῆσθαι.
> ἔνθεν ἔπειθ' ὁπόταν μὲν ἀπαΐξηι τέρεν αἷμα,
> αἰθὴρ παφλάζων καταΐσσεται οἴδματι μάργωι,
> εὖτε δ' ἀναθρώισκηι, πάλιν ἐκπνέει, ὥσπερ ὅταν παῖς
> κλεψύδρηι παίζουσα διειπετέος χαλκοῖο—
> εὖτε μὲν αὐλοῦ πορθμὸν ἐπ' εὐειδεῖ χερὶ θεῖσα
> εἰς ὕδατος βάπτηισι τέρεν δέμας ἀργυφέοιο,
> οὐδεὶς ἄγγοσδ' ὄμβρος ἐσέρχεται, ἀλλά μιν εἴργει
> ἀέρος ὄγκος ἔσωθε πεσὼν ἐπὶ τρήματα πυκνά,
> εἰσόκ' ἀποστεγάσηι πυκινὸν ῥόον· αὐτὰρ ἔπειτα
> πνεύματος ἐλλείποντος ἐσέρχεται αἴσιμον ὕδωρ.
> ὣς δ' αὔτως, ὅθ' ὕδωρ μὲν ἔχηι κατὰ βένθεα χαλκοῦ
> πορθμοῦ χωσθέντος βροτέωι χροῒ ἠδὲ πόροιο, —
> αἰθὴρ δ' ἐκτὸς ἔσω λελιημένος ὄμβρον ἐρύκει,
> ἀμφὶ πύλας ἠθμοῖο δυσηχέος ἄκρα κρατύνων,
> εἰσόκε χειρὶ μεθῆι, τότε δ' αὖ πάλιν, ἔμπαλιν ἢ πρίν,
> πνεύματος ἐμπίπτοντος ὑπεκθέει αἴσιμον ὕδωρ.
> ὣς δ' αὔτως τέρεν αἷμα κλαδασσόμενον διὰ γυίων
> ὁππότε μὲν παλίνορσον ἀπαΐξειε μυχόνδε,
> αἰθέρος εὐθὺς ῥεῦμα κατέρχεται οἴδματι θῦον,
> εὖτε δ' ἀναθρώισκηι, πάλιν ἐκπνέει ἶσον ὀπίσσω.
>
> All things breathe in and breathe out in the following way: all have bloodless tubes of flesh stretched out to the outermost threshold of the body, and at their mouths they are pierced with many furrows right through the furthest extremity of the skin; as a result, gore is concealed, but a good path is cut for the air by passageways. Whence thereupon whenever smooth blood darts away, air will rush in, seething with raging surge. But when the blood leaps up, the air blows outwards, just as when a

[66] Arist. *Cael.* 294b13-30 = DK 13 A 20; cf. [Arist.] *De sudore* 25-26; [Arist.] *Pr.* 2.1.866b9-14, which both use the *clepsydra* to argue the (somewhat odd) idea that we do not sweat when we hold our breath; cf. n. 177 below.

> girl, playing with a *clepsydra* of gleaming bronze and placing the tube of the pipe against her well-shaped hand, dips it into the smooth body of silver-white water—the deluge does not go into the vessel, but the mass of air, having fallen against the many perforations, prevents it from within, until she uncovers the dense stream. Then, however, when breath is falling out, the apportioned water enters. Thus, in the same way as when water holds down in the depths of the bronze, with the passageway of the channel blocked by the mortal skin, the air outside striving eagerly inwards holds back the deluge about the gates of the harsh-sounding neck, controlling its surface, until she lets go with her hand. Then, back again, in reverse from before, with the breath falling forward, the apportioned water runs down and out. Thus, in the same way, when smooth blood surging through the limbs leaps away inwards, immediately the breath of air returns, seething with a surge; but when the blood leaps up, an equal amount breathes back out (Emped. DK 31B100 = Arist. *Resp.* 473b9-474a6).

It is quite difficult to pin down just what is going on in this poetic comparison and how it is supposed to relate to the anatomy of the human body—and scholars have reached markedly different conclusions in this regard. The primary difficulty stems from the fact that Empedocles claims that the pores occur at the edge of the ῥινῶν, which can be taken as either the plural of ῥίς, 'nose'—in which case Empedocles is referring to 'furrows pierced at the furthest extremity of the nostrils'—or it can be taken as the plural of ῥινός, 'skin'—in which case he is referring to the pores of our skin to which blood vessels lead. In the first scenario, Empedocles would be describing how we breathe through our nose (and the *clepsydra* would potentially represent our lungs); in the second, he would be describing cutaneous breathing (and the *clepsydra* would represent our blood vessels).

Aristotle vacillates in his interpretation, suggesting at *De resp.* 473a15-26 that Empedocles is referring to the nostrils, but saying at 473b2-4 "[Empedocles] says that inhalation and exhalation occur through certain veins in which blood is present—although they are not full of blood; rather, they have passageways to the external air" [γίνεσθαι δέ φησι τὴν ἀναπνοὴν καὶ ἐκπνοὴν διὰ τὸ φλέβας εἶναί τινας, ἐν αἷς ἔνεστι μὲν αἷμα, οὐ μέντοι πλήρεις εἰσὶν αἵματος, ἔχουσι δὲ πόρους εἰς τὸν ἔξω ἀέρα]. In either case, however, the basic idea seems to be that when blood inside our internal "tubes of flesh" [σαρκῶν σύριγγες] (somehow) retreats into the interior of our body, it allows the air *outside* to push its way through the pores and into the empty space.[67] In turn, when blood (somehow) rushes back outwards towards the mouths of these pores, air is pushed back out into the exterior environment. I will return to the consequences that these "tubes" [σύριγγες] have on my argument.

There are only a finite number of conceivable interpretations of this passage, so we can go through each in turn to illustrate just how difficult it is to match Empedocles' simile with any plausible physical picture. First, as Diels does, we can take Empedocles to be describing cutaneous breathing alone.[68] In this case, the *clepsydra* would correspond to the veins, the perforations of the clay vessel would correspond to the pores of the skin and the *clepsydra*'s spout would be located somewhere inside the body (fig. 2):

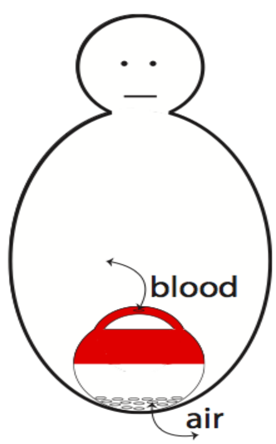

Fig. 2 Diel's Interpretation of Empedocles' *clepsydra* (cutaneous breathing)

[67] We would consider the air to be *drawn* in by vacuum pressure, not *driven* in; see below.

[68] Cf. Emped. DK 31 B 100, n. 16, for this interpretation. Diels argues that Aristotle is wrong to interpret ῥινῶν as nostrils, and he instead argues that Empedocles proposes only cutaneous breathing.

Blood rushing through the spout and into the internal cavities would allow air in through the pores, and blood rushing back towards the skin would push the air out. The problem with this interpretation is that, since it is water that flows in and out of the perforations of the *clepsydra* in the simile, not air, it forces us to take water in the *clepsydra* as the analogue of air in the body, while air in the *clepsydra* would represent blood in the body. This seems unnecessarily confusing, although were it not so, blood would have to represent air, and it would thus flow in and out of our pores as we breathed, just as the water does in the simile—a phenomenon as gross as it is unusual.[69] Lastly, if this interpretation were correct, Empedocles would be indicating that we breathe *solely* through our skin, and not through the mouth and nose as well. This seems a poor theory.

Furley puts forward a second interpretation, suggesting that the perforations of the *clepsydra* do in fact represent our pores, but the top spout is not located somewhere inside the body; instead, it represents our nose and mouth (fig. 3):[70]

[69] Empedocles may be facilitating the correspondence between air in the *clepsydra* with blood in the veins by claiming that the former "seethes with a raging surge" [παφλάζων οἴδματι μάργωι], which is a water-like thing for air to do; cf. n. 72 below.

[70] Furley 1957: 31-34. Even though this would only be implicit, it is perhaps playfully suggested by the metaphorical use of "at the mouths of the vessels" [ἐπὶ στομίοις] and the ambiguous valence of ῥινῶν. It is possible that Empedocles is incorporating them both poetically by blurring the categories of each side. This would be beautiful poetics, but does not make for an easy interpretation of the simile.

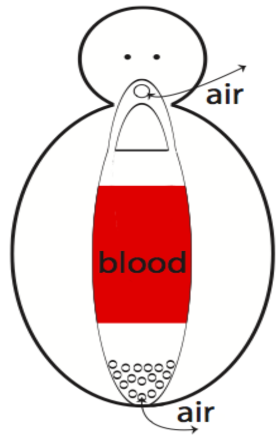

Fig. 3 Furley's Interpretation of Empedocles' *clepsydra* (cutaneous and mouth/nose breathing)

This interpretation would require that the 'bloodless veins' extend from our skin directly to our nose without any intervening organs and that air surrounds blood on either end of the tube. When air enters through the mouth and fills one end of the vein, it would push out the air on the other side, while the narrow pores at the skin would block the blood from escaping. When we exhale, the reverse would happen: air would re-enter through the pores and fill the veins, pushing air out through the mouth, until the blood reached the bottom of the windpipe. We would breathe insofar as blood oscillates back and forth inside our veins. There are several problems with this interpretation, not least of which is that it does not really correspond to Empedocles' simile at all, since water only flowed in through the bottom perforations and never came in through the top spout. Moreover, there is a single, not double action in the *clepsydra*.

Third, following Booth,[71] we can flip the *clepsydra* around inside the body, so to speak, so that the perforations correspond to hypothesized pores at the 'back of the nostrils' and the top pipe is stuck somewhere into the thorax, as though it were simply a vein (fig. 4):

[71] Booth 1960.

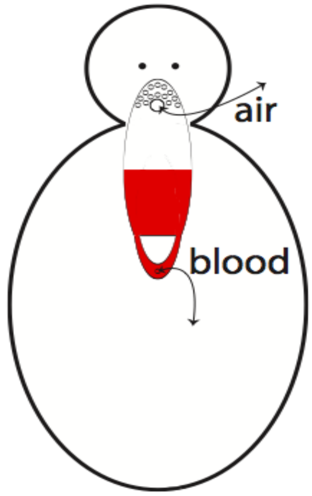

Fig. 4 Booth's Interpretation of Empedocles' *clepsydra* (nose breathing)

The spout would again be open to the interior of the body, just as it was in the first interpretation. Air would therefore pass through the perforations at the back of the nostrils and into the body, as the blood darted into the limbs. This, unfortunately, still requires that the air in the body would correspond un-intuitively to water in the simile, while air in the simile would correspond to blood. Moreover, the lungs would be left out.[72] In addition, blood would have to rush up through our throat, only to be stopped in our nostrils.

Our fourth option is to follow O'Brien and assume that the suggestive shape of the *clespydra* represents the lungs, and thus, the pores of the ῥινῶν must refer to pores in the surface of the 'skin' of the lungs, connected to veins within the body (fig. 5):[73]

[72] Booth 1960 argues that since water alone moves back and forth through the pores in the simile, it must be identified with the air in respiration, since air is the only thing that can pass through the perforations.

[73] O'Brien 1970.

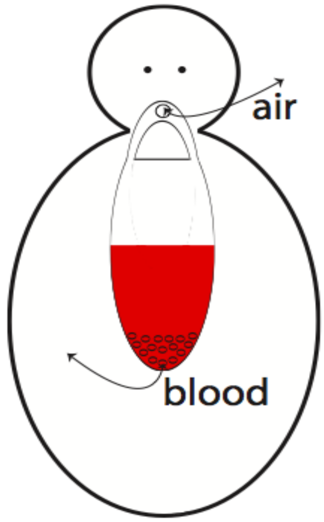

Fig. 5 O'Brien's Interpretation of Empedocles' *clepsydra* (mouth/nose breathing)

This avoids the correspondence of blood to air and air to water since the air coming through the top spout can actually correspond to air coming through the 'top spout' that is the windpipe. As such, when blood enters the lungs from the body—itself now conceived of as the water tank into which the young girl plunges the clepsydra—it would push air out through the mouth and nostrils. As blood darted from the lungs back into the chest cavity, it would draw in an equal amount of air. This is the conception that makes the most sense of the simile,[74] but despite its strengths, it almost completely ignores what Empedocles actually says, especially since: 1) blood would be passing through the pores that Empedocles has said hide the gore;[75] 2) the "furthest extremity of the skin" would be

[74] This interpretation does present the difficulty that blood would gush out of the mouth if we exhaled too strongly, since there would be no pores that prevent it from doing so.

[75] Emped. DK 31 B 100, ln. 4-5.

inside the body;[76] and most importantly, 3) Empedocles describes the transfer of air and blood in *veins*, not in the lung.[77]

All of these interpretations involve considerable problems; either they make no physiological sense or no textual sense. The simile is, at best, cumbersome and misleading. These difficulties have led Worthen to propose what should surely be the last viable option: to declare that it is simply misguided to try to make the clepsydra correspond closely to human physiology. Instead, Empedocles' merely wants to indicate that respiration involves the physical principle of mutual displacement (although Worthen still believes that Empedocles puts forth a model involving cutaneous breathing).[78] I follow Worthen's agnosticism, although I hold that Empedocles does not make the physical *principles* primary, but the technological analogue itself. The direct correlation with the body's anatomy does not seem to be at issue; rather, once Empedocles has supplied a technological analogue, it functions as the heuristic with which to conceptualize respiration. At that point, it is human physiology that needs to be negotiated with the technology, rather than the other way around. Once the simile has been made, it takes epistemological dominance over the physiology of the body, which becomes less important than the *clepsydra* in our understanding of respiration. Once he imports this implement, it allows him to think about the human body in certain ways, but at that point the technological simile takes over the position of reality, as it were. In this

---

[76] Emped. DK 31 B 100, ln. 2-3. However unlikely, this reading is possible since ἔσχατα τέρθρα, the "outermost threshold," can also potentially indicate the "innermost extremity," although this, to me, is a hard reading.

[77] Emped. DK 31 B 100, ln. 1-4. It is possible that Empedocles is referring to the bronchioles in the lung, when he speaks of 'bloodless tubes,' but then the shape of the *clepsydra* would be less consequential, since neither the air nor the blood would flow into a common vessel through the pores.

[78] Worthen 1970; cf. Harris 1973: 10-19, who is similarly agnostic.

way, 'to explain respiration' functionally means 'to find a comparable piece of technology.' Or, in other words, Empedocles is not merely using the *clepsydra* to think about the mechanism of breathing; he is letting the *clepsydra* stand in *as* the mechanism of breathing.

To confirm this interpretation, we can look to Empedocles' account of how we hear, which exhibits the same method by comparing the ear to a bell:

> τὴν δ᾽ ἀκοὴν ἀπὸ τῶν ἔσωθεν γίνεσθαι ψόφων, ὅταν ὁ ἀὴρ ὑπὸ τῆς φωνῆς κινηθεὶς ἠχῇ ἐντός. ὥσπερ γὰρ εἶναι κώδωνα τῶν ἴσων ἤχων τὴν ἀκοήν, ἣν προσαγορεύει σάρκινον ὄζον· κινουμένην δὲ παίειν τὸν ἀέρα πρὸς τὰ στερεὰ καὶ ποιεῖν ἦχον.
>
> And hearing he says comes from internal sounds, whenever air has been set in motion by a voice and echoes within. For, he says, the ear is just like a bell of equal echoes, and he calls it a 'fleshy shoot.' He says that the bell is moved and drives the air towards the solid parts and makes an echo (Emped. DK 31A86, ln. 27-30, B 99 = Theophr. *De sens.* 9).

The simile is relatively easy to understand: a voice sets the air in motion, which strikes the "bell" of the ear and causes it to resound in "equal echoes." This pushes the air further into the ear and toward the "solid parts" (presumably in the interior of the ear), which causes an internal echo in turn. Although the simile is comprehensible, we ought to note that it differs from Empedocles' general explanation of the senses, which describes all perceptions as the result of external corpuscles fitting into appropriate-sized pores in the organs.[79] By contrast, in the bell-model, air does not 'fit into' the sound-pores, since it is driven into the ear. Moreover, a sound occurs when it strikes the *solid parts*, not any waiting pores. In sum, Empedocles provides a technical simile as a way to explain a sense organ, even though it conflicts with other aspects of his theory. It seems that these technologies exert a certain type of cognitive attraction that leads Empedocles to

[79] For a full account of Empedocles' pore-theory of perception, see section 3.1.

incorporate them into his assumptions about the body, even if they do not fit particularly well with his other physiological commitments.

In this regard, he epitomizes the tendency to let technologies function as quasi-theories in their own right and to let comparisons slip into direction descriptions. I have called this tendency analogic drift. To be sure, Empedocles writes poetic philosophy, which perhaps encourages a certain laxness and figuration when providing vivid descriptions of physical mechanisms. As we shall see, however, while he presents an extreme example of this cognitive habit, he inaugurates a long tradition of scientific theorists who—whether consciously or not—do something quite similar. I have therefore begun with Empedocles not only because he is one of the earliest members of the Greek scientific tradition, but also because he helps establish a clear model through which we can investigate other instances of technologies shaping theories, even if these occurrences are more hidden, subtle and nuanced.

1.2 Dual Function Blood Vessels and Modal Heuristics

Having established how Empedocles uses a technological implement to understand how the veins operate in *respiration*, we can turn to a broader history of those who treat these vessels as vehicles of blood-*distribution*. Although we may find it more familiar to understand the function of the veins in this way, there is nevertheless a curious feature displayed by almost every account of the blood vessels in the fifth and fourth centuries BCE: despite the fact that theorists operate with vastly different physiological ideas, almost every single author takes it for granted that both blood [αἷμα] and air [πνεῦμα] flow through the same vessels at the same time. For instance, Alcmaeon distinguishes a special class of "blood-flowing veins" [αἱμόρροι φλέβες] into which blood can retreat as it exits from other vessels (which suggests that other veins are not solely for blood);[80] Diogenes of Apollonia argues that *pneuma*—the substance he holds responsible for thought—travels around the body through the blood vessels;[81] Philistion, a contemporary of Plato, describes health as the unobstructed flow of *pneuma* throughout the body, disease being caused by its blockage.[82] Similar ideas persist in multiple other texts. For instance, Aristotle simply mentions how large blood vessels have more air in them, which makes them cold:

> παραπλησίως δὲ καὶ ἐπὶ τῶν φλεβῶν καὶ ἐπὶ τῶν κοιλιῶν ἔχει· ψυχραὶ γὰρ αἱ μεγάλαι φλέβες καὶ κοιλίαι. ὥσπερ γὰρ ἐν μικρῷ καὶ ἐν μεγάλῳ οἰκήματι τὸ ἴσον πῦρ ἧσσον ἐν τοῖς μείζοσι θερμαίνει, οὕτω κἀν τούτοις τὸ θερμόν· ἀγγεῖα γὰρ καὶ ἡ φλὲψ καὶ ἡ κοιλία. ἔτι δ' αἱ ἀλλότριαι κινήσεις ἕκαστον τῶν θερμῶν καταψύχουσιν, ἐν δὲ ταῖς εὐρυχωρεστέραις τὸ πνεῦμα πλεῖον καὶ ἐνισχύει μᾶλλον·
>
> A very similar thing applies to the veins and the cavities (of the heart); for large veins and cavities are cold. Just as an equal-sized fire heats larger rooms less in both a large and a small house, heat behaves in the same way in these (body parts) as well; and veins and cavities are also vessels. Still, external motions cool hot things, and in larger (vessels) there is more air, and it has a greater effect (Arist. *Part. an.* 667a23-25).[83]

Several Hippocratic authors present similar ideas. For instance, the author of *On the Sacred Disease* describes a physiological system that includes the distribution of sense-

---

[80] Alcmaeon, DK 24 A 18 = Aët. 24.1; cf. Harris 1973: 8.

[81] Diog. Ap. DK 64 B 6 = Simpl. *In phys.* 153.13; Arist. *Hist. an.* 2.2.511b-512b12; cf. Harris 1973: 25-27.

[82] *Anon. Lond.* 20.43-50; cf. Harris 1973: 19-20, 36-38.

[83] Aristotle grants several different physiological roles to *pneuma*, including in sensation, growth and motion. At *GA* 5.8.789b6-13, he even calls *pneuma* a multi-purposed instrument (for discussions of these multiple uses, see Peck 1953; Nussbaum 1978). For the purposes of this chapter, I will focus solely on *pneuma* as it relates to the vascular system.

causing *pneuma* throughout the body's passageways.[84] According to this text, air enters through inhalation and passes through the vessels of the neck on its way to the brain. Here, it 'deposits the *acme* of intelligence.'[85] Then, after having imparted its sense-giving nature, the air splits into two, some entering the lungs and veins directly, and some traveling first to the abdomen and then to other parts of the body *via* the veins in turn [κατὰ τὰς φλέβας].[86] Epileptic fits occur precisely when phlegm, which is cold by nature, blocks the flow of *pneuma* to the brain. If ever the air is blocked in any of our veins, it leads to paralysis:

> κατὰ ταύτας δὲ τὰς φλέβας καὶ ἐσαγόμεθα τὸ πουλὺ τοῦ πνεύματος· αὗται γὰρ ἡμέων εἰσὶν ἀναπνοαὶ τοῦ σώματος τὸν ἠέρα ἐς σφᾶς ἕλκουσαι, καὶ ἐς τὸ σῶμα τὸ λοιπὸν ὀχετεύουσι κατὰ τὰ φλέβια, καὶ ἀναψύχουσι καὶ πάλιν ἀφιᾶσιν. οὐ γὰρ οἷόν τε τὸ πνεῦμα στῆναι, ἀλλὰ χωρέει ἄνω καὶ κάτω· ἣν γὰρ στῇ που καὶ ἀποληφθῇ, ἀκρατὲς γίνεται ἐκεῖνο τὸ μέρος ὅπου ἂν στῇ· τεκμήριον δέ· ὁκόταν καθημένῳ ἢ κατακειμένῳ φλέβια πιεσθῇ, ὥστε τὸ πνεῦμα μὴ διεξιέναι διὰ τῆς φλεβὸς, εὐθὺς νάρκη ἔχει.
>
> Through the veins we lead in the majority of our air. These are the vents of our body, drawing air into themselves; and they *channel* it to the rest of the body through the small veins and cool it; then they send it back out again. For the air is unable to stagnate, but flows up and down. For if it stagnates anywhere and is cut off, that part becomes powerless. Here is proof: whenever little veins are compressed when someone is sitting or lying down, and the air does not travel through the vein as a result, immediately numbness takes hold ([Hippocr.] *De sacr. morb.* 4.1-2, emphasis mine).

For this Hippocratic author, in a healthy body both air and the humours somehow manage

[84] [Hippocr.] *De flat.* 7.21-25, 8.41-49, 10.1-48, 14.1-64; *De nat. os.* 11, 13-18. Due to the presence of a quotation from Aristotle and the inclusion of the work in the list of Hippocrates' writing by Bachhaeus of Tanagra in 200 BCE, *De nat. os.* must have been written either in the latter half of the fourth, or some time in the third century BCE; cf. Harris 1973: 51. For a fuller discussion of the various forces at play within Hippocratic physiological models, see Gundert 1992: 458-462; Duminil 1983: 79-82.

[85] [Hippocr.] *De. morb. sacr.* 16.10; cf. 7.3-5. It is unclear precisely what this means. For a discussion of this problem, see Lo Presti 2008, esp. chapter 3.

[86] [Hippocr.] *De. morb. sacr.* 16.3.

to flow in the same vessels without interruption. Dual function constitutes its normal state.

To be sure, ancient theorists from a variety of disciplines employ the concept of *pneuma* in manifold ways, and a related philosophical idea appears already in Anaximenes, who posited that air [ἀήρ] is the constituent element of all things. Natural philosophers and physicians variously considered 'air' or 'breath' the basic life force in the body, the vehicle of heat, a cooling force, the vehicle of sensation, the vehicle of thought and the substance responsible for motion. The Stoics brought *pneuma* to the forefront of their physical account of the world, considering it the life force of the universe as a whole and suggesting that its tension holds all things together (while also linking *pneuma* to fire).[87] Thus, I am not suggesting that *pneuma* functioned in the same way in all these theories (or that these theorists thought of it as a substance with the same qualities), simply that in the fifth and fourth centuries BCE in particular, accounts of the vascular system treat *pneuma* as a substance beholden to certain physical behaviours. Most importantly, whether these particular theorists hold *pneuma* to be responsible for sensation, disease or heat regulation, they consistently assume that it moves through the same passageways as the blood.[88] That is, as this above passage suggests, they treat the veins as though they are both vents for air [ἀναπνοαί] and channels for blood [ὀχετοί] at the same time. Veins almost always display this double function.[89]

---

[87] Cf. section 5.4. Moreover, there was also a *Pneumatic* medical school in the Hellenistic era that formed an alternative to humoural medicine; cf. Wellman 1895.

[88] Sometimes medical theorists require that air follows a downward course, while in other instances they presume that it moves upwards according to the natural tendency of hot, light substances to rise.

[89] Although one could argue that ancient medical theorists believed that air and blood flowed in the same veins because they knew only one set of vessels, I would argue that these authors were not yet looking for another set of vessels to solve the problem of dual function veins—precisely because they did not see this

Due to the prevalence of this idea, it has received much scholarly attention. That being said, commentators have not sufficiently addressed the strangeness of double-function veins. To our modern minds it seems obvious that air and blood cannot flow smoothly in the same pipe—especially if that pipe moves up and down, ascending and descending across uneven terrain as it curves along the various contours of the body. In such a system, air pockets would form that would capture blood just like the trap in a kitchen sink. Bubbles would develop. Blood would pool at our feet. If we lifted our arm, blood would immediately drain out of it. Despite such difficulties, however, the double function of the veins was an extremely common idea, often assumed without argument. Certainly, ancient medical thinkers describe blockages and clogs. For instance, along with the consequences of blockage seen in *On the Sacred Disease* above, Praxagoras talks about "bubbles" rising up from the feet and causing both mania and epilepsy,[90] and Philotymius, Praxagoras' pupil, mentions bubbles arising from the process of digestion.[91] Nevertheless, these are *pathologies*. In a healthy body air and blood would flow through the same vessels at the same time without interruption.

In order to understand why this double function was such a compelling idea, we can turn to the technological context of these theories, especially since, as the metaphor of 'channeling' [ὀχετέουσι] suggests, the Hippocratic author of *On the Sacred Disease*

dual function as a problem. Praxagoras (b. c. 340 BCE) was the first theorist to argue that the arteries contained air, while the veins contained blood, although Alcmaeon may have hinted at a similar distinction (see above); cf. Longrigg 1988: 467; von Staden 1989: 173. Herophilus (b. c. 320 BCE) was the first to make an *anatomical* distinction between veins and arteries, and he also discovered the nerves. See sections 2.0 and 2.1 below; cf. Harris 1973: 24; Longrigg 1988: 462-471; von Staden 1996.

[90] Praxag. *AMG* fr 19. He makes a distinction between exterior πνεῦμα and that which activates the body, which is 'breath-like' [ἀτμῶδες]; cf. Gal. *An in art.* 2 K. 4.707; cf. Harris 1973: 112.

[91] See Oribasius, *Coll. Med.* 5.22 *CMG* 6.1.151.

imagines that the veins somehow work like an irrigation system.[92] In fact, multiple authors use this comparison, and it provides the key to understanding why so many ancient medical authors conceive of blood-delivery as they do. For instance, while describing how blood travels around the body in both *De partibus animalium* and *Historia animalium*, Aristotle likens the veins to channels [ὀχετοί] and irrigation systems [αἱ ὑδραγωγίαι].[93] Plato too uses this analogy of an irrigation system [ἡ ὑδραγωγία] when explaining the distribution of blood,[94] which he believes provides nourishment for the body, having been derived from food that gets divided up in the stomach.[95] He compares the veins to 'channels' [ὀχετοί] and 'conduits' [αὐλῶνες]:

> ὁπόταν γὰρ εἴσω καὶ ἔξω τῆς ἀναπνοῆς ἰούσης τὸ πῦρ ἐντὸς συνημμένον ἕπηται, διαιωρούμενον δὲ ἀεὶ διὰ τῆς κοιλίας εἰσελθὸν τὰ σιτία καὶ ποτὰ λάβῃ, τήκει δή, καὶ κατὰ σμικρὰ διαιροῦν, διὰ τῶν ἐξόδων ᾗπερ πορεύεται διάγον, οἷον ἐκ κρήνης ἐπ' ὀχετοὺς ἐπὶ τὰς φλέβας ἀντλοῦν αὐτά, ῥεῖν ὥσπερ αὐλῶνος διὰ τοῦ σώματος τὰ τῶν φλεβῶν ποιεῖ ῥεύματα.
>
> For whenever respiration goes in and out and the internal, attached fire follows, this fire always rises though the abdomen, entering in and taking hold of the foods and drinks and indeed it dissolves them, and dividing them up into small parts, it leads them through the outlets by which it travels and draws them off to the veins, just as (water) from a spring into channels; and it makes the streams of the veins flow through the body as though through a conduit (Pl. *Tim.* 78e5-79a5).

As we shall see, rather than simply supplying a colourful image, this analogy between veins and conduits substantially shapes the way these thinkers conceptualize both the blood vessels and the mechanism of blood distribution itself. In order to evaluate this, however, it stands to reason that if multiple Greek theorists compare the veins to

[92] Cf. [Hippocr.] *De nat. os.* 13, 16, 19; *De cord.* 7.

[93] Arist. *Part. an.* 3.5.668a14-17; *Hist. an.* 515a23-24.

[94] Pl. *Tim.* 78a1.

[95] Pl. *Tim.* 80e4-81a5.

channels, pipes and irrigation systems, while also paradoxically considering these to be vents, it might be fruitful to take a look at their pipes.

Ancient Greek pipelines, specifically domestic water delivery systems of the fifth century BCE, display a significant feature: the majority were composed of short sections of terra cotta pipe about 20-25 cm in diameter and 60 cm long[96]—presumably restricted by the length that could be handled on the potter's wheel. These sections were fit together using their male and female ends and then sealed with mortar. Most importantly, each section had a hole cut in the top, which was then covered back over with a close-fitting lid (fig. 6):

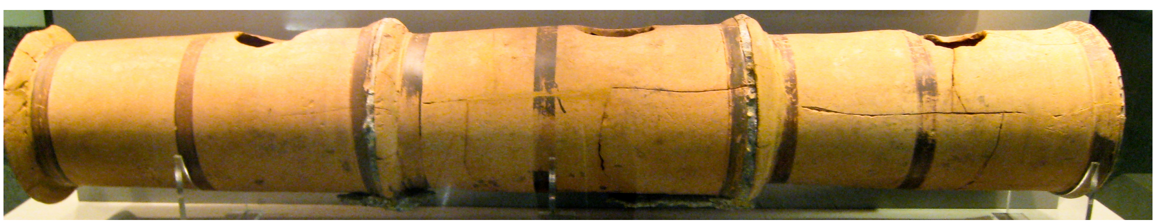

Fig. 6 Terracotta Pipes of the Peisistratid Aqueduct. Found during subway construction and displayed at Syntagma station, 5th century BC. Image from Wikimedia Commons, photo credit to Sharon Mollerus.

This design most likely allowed the pipefitter to reach inside to seal the joint, although it has been suggested that these holes may have instead simply allowed for cleaning.[97] Regardless of their purpose, however, the consequence of the design remains the same:

[96] Hodge 2000: 41; 2002: 25; cf. Thomson and Wycherley 1972: 197-198, who approximate pipe lengths at 30 cm in diameter; Wilson 2008: 293-296 gives the internal diameter as 15-25cm. If Greek water engineers wanted to increase capacity, they would have increased the number of pipes, not their size. Greek water supply systems, however, did not rely on pipelines alone, but also employed wells, and bottle cisterns. For a general account of Greek water supply systems, see Thomson and Wycherley 1972; Hodge 2002: 25-31, 48-66; Crouch 1993; Jansen 2000; Wilson 2000, 2008: 285-318; Humphrey 2006: 35-51. See also Bruun 2000: 557-573, who examines the legislation relating to water distribution in the Greek world. For other aspects of ancient water technology, see Wikander 2000.

[97] Scholars disagree about the purpose of the holes; cf. Tölle-Kastenbein 1991, 1994: 71-72; Fahlbusch 1994: 109; Hodge 2000: 41; Jansen 2000: 106.

these pipes could not have run at pressure. With a potentially leaky outlet at the top of the pipe, water could have only filled some of the passageway, while air must have filled the rest.[98] The system could therefore have no real flow control and did not incorporate valves to shut off the water at any given point except at its source. Instead, these water-delivery systems relied solely on gravity-flow to maintain constancy. Air and water flowed in the same pipes.

If this is the technological context in which ancient physiologists lived in the fifth and fourth centuries BCE, when they thought about blood distribution and used their water distribution systems as a conceptual analogue, it was natural for them to assume that both blood and air flowed in the same vessel simultaneously. In fact, since the water distribution technology around them worked in exactly this manner, it might actually have been odd for them *not* to think in this way. And indeed, once the metaphor is employed, it is a convincing enough comparison to suggest that the blood distribution system must function in the same way. Irrigation's very persuasiveness as an appropriate analogue allows Greek pipe technology to take epistemological precedence over even basic physiology, just as the *clepsydra* did for Empedocles. I am not suggesting that no mechanisms were available that would have suggested the problems with such a system, simply that when importing irrigation as a heuristic analogy, ancient medical theorists thought with their own pipes, not ours.

We can see this conceptual reliance on contemporary pipes with Plato, when he explains the blood vessels. Not only does he propose that both air and blood flow in the

[98] Hodge 2002: 25 notes that calcium deposits occur only in the bottom half of ancient pipes, notably the *Enneakrounos* pipeline in Athens. This supports the conclusion that they did not run full; cf. Tölle-Kastenbein 1994, 1996; Wilson 2008: 294. There is some evidence that the varying levels of terrain in Athens caused a short section of pipeline to run under very slight pressure, although even this debated; cf. Hodge 2000: 42; Jansen 2000: 108.

same vessels, he also argues that the entire mechanism of blood propulsion operates in the same way as the gravity-fed irrigation channels around him:

> ταῦτα δὴ τὰ γένη πάντα φυτεύσαντες οἱ κρείττους τοῖς ἥττοσιν ἡμῖν τροφήν, τὸ σῶμα αὐτὸ ἡμῶν διωχέτευσαν τέμνοντες οἷον ἐν κήποις ὀχετούς, ἵνα ὥσπερ ἐκ νάματος ἐπιόντος ἄρδοιτο. καὶ πρῶτον μὲν ὀχετοὺς κρυφαίους ὑπὸ τὴν σύμφυσιν τοῦ δέρματος καὶ τῆς σαρκὸς δύο φλέβας ἔτεμον νωτιαίας, δίδυμον ὡς τὸ σῶμα ἐτύγχανεν δεξιοῖς τε καὶ ἀριστεροῖς ὄν· ταύτας δὲ καθῆκαν παρὰ τὴν ῥάχιν, καὶ τὸν γόνιμον μεταξὺ λαβόντες μυελόν, ἵνα οὗτός τε ὅτι μάλιστα θάλλοι, καὶ ἐπὶ τἆλλα εὔρους ἐντεῦθεν ἅτε ἐπὶ κάταντες ἡ ἐπίχυσις γιγνομένη παρέχοι τὴν ὑδρείαν ὁμαλήν.
>
> Indeed, when our Superiors had implanted all these kinds as nutriment for us inferior creatures, they channeled through our body itself, cutting channels in gardens, as it were, so that our body might be irrigated just as from an inflowing spring. And first, they cut hidden channels underneath the natural junction of the skin and flesh along the spine, on the grounds that the body happened to be double, with rights and lefts. They led these channels down along the backbone, keeping the generating marrow between them, so that this might thrive as much as possible, *and so that the moisture, insofar as it went downwards, might provide even irrigation to the rest by flowing from there* (Pl. *Tim.* 77c6-d8, emphasis mine).

In this passage, Plato does not simply use irrigation as a convenient comparison to illustrate an already formed physiological model. Rather, he lets irrigation function as his primary heuristic, even adopting gravity-flow as the main mechanism of propulsion for the vascular system. He is not alone in this. A gravity-flow model of the blood vessels seems implicit in the fact that the Hippocratic author of *On the Nature of Man* (most likely Polybus) suggests that the thick blood vessels descend from the head.[99] In fact, in *Historia animalium*, Aristotle claims that "all [other writers] identify the source of [the veins] as in the head and the brain" [πάντες δ' ὁμοίως τὴν ἀρχὴν αὐτῶν ἐκ τῆς

[99] [Hippocr.] *Nat. Hom.* 11. Yet, like Plato, this author also adds at 11.40-46 that veins from the stomach carry nourishment all over the body; cf. n. 102 below. For a description of Polybus' account, see Arist. *Hist. an.* 3.3.512b11-513a2; cf. Arist. *Hist. an.* 3.2.511b24-30 = [Hippocr.] *De nat. os.* 8 for similar ideas.

κεφαλῆς καὶ τοῦ ἐγκεφάλου ποιοῦσι].[100] Although this is an overstatement, it indicates how common the idea that blood *descended* from above was, thus implicitly relying on gravity-flow as a propulsion mechanism.[101] Yet, despite its widespread acceptance, this idea presents a particular problem for Plato's greater physiological theory, since he elsewhere proposes that the blood is manufactured in the stomach, which sits below at least half of its delivery points. Even the heart, which he considers the fountain-spring of the veins [πηγή], sits below the brain.[102] Gravity-flow alone simply cannot account for complete blood distribution, since it cannot explain how blood flows upwards—let alone in a system where the veins are both vents [ἀναπνοαί] and channels [ὀχετοί] at the same time. For Plato, the very comprehensibility of the technological analogy trumps its applicability. He thus allows the analogue to stand in for the target field he seeks to explain, and the comparison causes Plato to transfer two features of Greek pipes into a physiology that is simply not the same as garden irrigation and cannot work by gravity-flow alone. In other words, the technology does not *explain* a theory of the body; it predicates physiological assumptions. The heuristic that the technology supplies functions as a type of theory in its own right.

However reliant upon (or at least implicated in) technological environments these thinkers appear to be, it is not as though natural philosophers of the fifth and fourth centuries BCE were simply ignorant of the physical principles required to predict that bubbles and pooling would occur in dual function, blood-distributing veins. As the above

---

[100] Arist. *Hist. an.* 3.3.513a10-12.

[101] For the chief Hippocratic descriptions of the blood vessels, see *Epid*. 2.4.2, 2.4.10 = *De. nat. os.* 10; *Nat. Hom.* 2 = *De nat. os.* 9; *De morb. sacr.* 3; *De carn.* 5; cf. Jouanna 1999: 311, who notes that all these accounts are slightly different.

[102] Pl. *Tim.* 78e5-79a5 focuses on the stomach's role in manufacturing the blood, while *Tim.* 70b1 treats the heart as the source of the veins; cf. [Hippocr.] *De nat. os.* 2.

example from Empedocles shows, they were well aware of mutual displacement and could employ it in their physiological models. Yet, as I noted, when discussing air transfer and using the *clepsydra* as an analogue, Empedocles does not represent the veins as the *channels* of the body [ὀχετοί]; rather, he compares them to *tubes* [σύριγγες].[103] He is not the only thinker who figures the veins in this way while utilizing the mutual displacement of blood and air in order to explicate breathing. Plato seems to have adopted a similar model. In fact, despite establishing a blood-delivery system which functions on non-pressurized gravity-flow, when explaining respiration he relies on pressurized mutual displacement—perhaps even while speaking about the *same veins.*

Plato's basic model works on the idea of "reciprocal propulsion" [περίωσις],[104] where air is not drawn, but *driven* into the body through the nose/mouth and the pores in succession. He posits that the body contains two particulate mesh-works of fire, one sitting at the bottom of the windpipe, which separates the lungs from the external air, and the other sitting at the top of stomach, which does the same for this organ. These mesh-works act as filters that allow smaller elements, like fire and air, to pass inwards, but prevent water and earth from exiting the body. Similarly, he considers the skin itself to be yet another giant meshwork, which allows air into the blood vessels through the pores, but does not allow blood back out. He compares these filters to wicker "fish baskets" [κύρτοι] used to strain water for fish.[105]

[103] The word σῦριγξ originally refers to a shepherd's pipe, presumably made out of a reed; see *Il.* 10.13, 18.536. Since this reed can be sealed by the fingers or used to draw up liquid as though a straw, it takes on the secondary meaning of 'tube,' although this fragment of Empedocles the first extant passage where the word is used to describe something that transports liquid; cf. entry in *LSJ.*

[104] Pl. *Tim.* 79c6.

[105] Pl. *Tim.* 78b2-6.

For Plato, when we breathe, air moves into the body *via* the windpipe, passes through these mesh-works and enters the lungs. The heat of the blood then warms the air until it grows hot, at which point it flows back up the windpipe so as to reach its proper place in the fiery cosmic *aether* according to the idea that "heat, according to its nature, moves to its own place outside, towards what is kindred" [τὸ θερμὸν δὴ κατὰ φύσιν εἰς τὴν αὑτοῦ χώραν ἔξω πρὸς τὸ συγγενὲς ἰέναι].[106] When the air is driven out of the body, however, it enters into the surrounding atmosphere—which is *itself* conceived of as an enclosed, finite space (not unlike a rigid *clepsydra*). Therefore, since the air coming out of the lungs must somehow be accommodated in the greater atmosphere (which can neither expand, nor compress), it ends up driving a portion of the external air back into the body through the pores and thus *back into the veins*. The fire in the blood then heats this new air, at which point it too seeks its natural place. It exits through the pores and thus drives more external air back into the lungs through the windpipe to start the whole process again. This completes Plato's reciprocating system, "as though a wheel rolling one way and returning back."[107] In sum, when conceptualizing the mechanism of *blood-delivery*, Plato utilizes gravity-flow and double-function veins; when explaining *respiration* he relies on the impossibility of a void [κενὸν οὐδέν ἐστιν],[108] the mutual displacement of both air and blood and the attraction of 'like for like.' Although his physiology of blood-delivery presumes that air and blood flow can harmoniously in the same veins, his physiology of respiration relies on these two substances constantly displacing each other. What is most important, Plato does not give any indication that the

[106] Pl. *Tim.* 79d7; cf. Solmsen 1968b for a full account of Plato's theory of respiration.

[107] Pl. *Tim*. 79e4-11; cf. Arist. *Resp.* 472b6-23, which presents a summary of Plato's model.

[108] Pl. *Tim.* 79b1; cf. 79b10.

veins fulfilling these two functions *are actually different sets of vessels*. He does not put up a partition between two separate systems. Instead, he simply repurposes the same vessels for another bodily function, even when these physiologies are mutually exclusive. He applies alternating modal heuristics.

From the above evidence, however, it is clear that while constructing his model of respiration Plato does not simply rely on analogies with existing implements, but employs physical principles. Therefore, while the irrigation analogy sets up a *technological* heuristic, the conceptual framework used to explain respiration relies on more than just a single tool. At the same time, however, the Greek scientific tradition justifies the non-existence of a void surprisingly often by using either the *clepsydra* or the wineskin as evidence.[109] As such, when Plato employs this particular principle, we should check whether he is relying on just such an implicit technological heuristic for conceptual support. As it turns out, several aspects of his theory illustrate that although he never explicitly employs the simile of the *clepsydra*,[110] he implicitly creates his physiological model of respiration with this technology in mind—even as he cites abstract principles for justification. In fact, his abstract principles are embodied in this device, and when he thinks about the non-existence of a void, he tacitly uses the *clepsydra* to do so.

We can see this in two related ways. First, in order for Plato's model to work, the lungs—indeed, the whole of the chest—would need to be a rigid body. If this were not the case, the air rushing into the body during inhalation would simply result in the expansion of the chest (not unlike an inflatable windbag), and no air would need to be

[109] For instance, even more than three hundred years later, Hero (c.10-70 CE) still uses the *clepsydra* to establish whether there is a vacuum in nature (*Pneum.* 1.2).

[110] If Plato did make the comparison explicit, it would be slightly out of place, since the *clepsydra* does not function on heat.

pushed out of the pores. Second, were the chest not implicitly modeled on a rigid body, the reduced size of the chest after exhalation would offset the volume of the newly exhaled air (not unlike a deflated windbag); the surrounding atmosphere would not need to accommodate any new material, since the reduced volume of the collapsed chest would have already compensated for it. No air would need to be 'driven round' into the pores. Thus, despite ostensibly employing abstract principles, Plato's physiological model actually requires that the chest functions in a way similar to the rigid *clepsydra*—even when this does not conform particularly well with either human physiology or empirical observations. Although his descriptions include veins, his model functions as though the whole body itself were a large, ceramic cavity. In this way, a technological implement has come to stand in for a physical process, anchoring a heuristic through which Plato derives his basic assumptions about the behaviour of the body.

For Plato, then, there are two separate explanatory frameworks, employed in alternation to explicate two related physiological aspects: one uses pneumatic water technology and mutual displacement to explain how air is drawn into the veins; this conceptualizes the veins as tubes [σύριγγες]; the other uses gravity-fed dual function conduits to explain blood-delivery; this construes these same veins as channels [ὀχετοί]. His heuristics establish two mutually exclusive physiologies modeled on two different technologies, even as he talks about the same body parts.

What are the consequences of this for our understanding of theory-formation in ancient science? To begin, we can note that when explaining these two different physiological processes of the body, Plato does not look at the *body* first and then try to find a suitable explanation to account for all the relevant features, nor does he simply invoke a general principle of *horror vacui* and then see how it applies to the particular physiology of the veins. Rather, he adopts parallel technologies as cognitive tools and then tries to conform the body to the parameters set by the comparison. That is, when he needs to explain how air is transferred, he implicitly relies on a technology that transfers air; when he needs to explain blood-delivery, he relies on a technology that delivers water. At different times, he needs to explain different aspects of the body and employs different, localized heuristics in order to do so.

1.3 Aristotle's Heart and Competing Heuristics

The dissonance among multiple competing technological analogues is not unique to Plato; Aristotle's explanation of the respiratory and vascular systems presents a similar tension: he too assumes that both *pneuma* and blood flow in the same vessels during blood-distribution, while he relying on pressurized air-transfer for respiration.[111] And, like Plato, he uses two different technological analogies to support these heuristics. His account is far more detailed that Plato's, though, insofar as he makes the heart, lungs and vascular systems part of multiple physiological operations, including blood production and distribution, respiration and heat regulation, sleeping and waking, and movement and sense perception. To account for these various processes, he incorporates different temperatures and purities of blood, different types of and roles for *pneuma*, and intricate

[111] It is possible that Aristotle conceives of *pneuma* and blood as intermingled substances, especially since he introduces the concept of 'innate *pneuma*' [σύμφυτον πνεῦμα]; cf. Arist. *Part. an.* 659b17; 669a1; *Gen. an.* 744a3; 781a24; *De motu an.* 703a10-15; *De somn.* 456a12; [Arist.] *De spirit.* 481b19; 482a33. Yet, despite this possibility, when Aristotle discusses how *pneuma* moves about the body, he treats it as independent matter, flowing separately from the blood. Thus, even if it retains the potential to be thought of as a co-ordinate and blended, in practice, Aristotle does not treat it as such.

anatomical details of the vascular passageways.[112] Despite his increased sophistication, however, Aristotle displays the same conceptual tendency we saw with Plato, namely to see respiration as functioning in pressurized vessels, while imagining the blood-delivery system as composed of non-pressurized dual function veins. Moreover, he employs two additional analogues to explicate two features the heart itself, even though these comparisons predicate contrary behaviours. In other words, even while Aristotle presents a complex physiological system based on observations, anatomical investigations and logical arguments, he too still utilizes the technologies around him as touchstones on which to structure multiple assumptions about the body.

Aristotle's account of respiration extends across multiple texts, including *De partibus animalium*, *Historia animalium*, *Generatione animalium* and *De somno*.[113] It is *De respiratione*, however, that contains his longest treatment. In this treatise, he asks what purpose breathing serves for all animals, including birds, frogs, insects and fish. He notes that not all these creatures breathe air, but nevertheless, they still have analogous organs. Thus, the purpose of breathing must be to regulate innate heat rather than to supply substance, and the respiratory organs must serve as a type of cooling system.[114] In fact, Aristotle argues that life itself relies on this system, since the nutritive function—the most basic element of life—depends on the regulation and conservation of heat in the body.[115] With this overall purpose in mind, he attempts to explain the actual mechanism

---

[112] Arist. *Part. an.* 667a1-6.

[113] For a full account of these texts and their relation to each other, see Harris 1973.

[114] Arist. *Resp.* 471b23-29; 476a7-14. He cites our need to breathe more when we are hot and notes that air is cooler when it is inhaled than when it is exhaled.

[115] Without heat the stomach could not digest food and, ultimately, help produce blood; cf. Arist. *Resp.* 474a25-b9. Yet, whereas we might deem the *loss* of heat to be what threatens death, Aristotle actually

of breathing to see how it functions as part of these larger physiological mechanisms. To do so, he points to a basic physiological fact for which Empedocles and Plato both failed to account: the chest rises upon inhalation.

Aristotle argues that as the chest expands, it draws air inwards. In order to support and explain his argument, Aristotle invokes the first of our technological analogues, comparing the action of the lungs to the action of bellows in a forge:

> ἄραντες μὲν γὰρ τὸν τόπον, καθάπερ τὰς φύσας ἐν τοῖς χαλκείοις, ἀναπνέουσιν (αἴρειν δὲ τὸ θερμὸν εὔλογον, ἔχειν δὲ τὸ αἷμα τὴν τοῦ θερμοῦ χώραν)· συνιζάνοντες δὲ καὶ καταπλήττοντες, ὥσπερ ἐκεῖ τὰς φύσας, ἐκπνέουσιν. πλὴν ἐκεῖ μὲν οὐ κατὰ ταὐτὸν εἰσδέχονταί τε τὸν ἀέρα καὶ πάλιν ἐξιᾶσιν, οἱ δ' ἀναπνέοντες κατὰ ταὐτόν.
>
> People inhale by raising that region [of the chest], just as bellows in a forge (and it is logical for heat to raise it, and for blood to have the place of heat); and just as with the bellows, people exhale by collapsing and pushing [that region] down—except that in the case of the bellows, they do not receive and expel the air in turn *via* the same passage, whereas those breathing do use the same passage (Arist. *Resp.* 474a12-17).

Unlike Empedocles, Aristotle does not leave his comparison open and underdetermined with respect to its physiological implications; rather, he closely delineates the differences between lung and its analogue: breath comes in and exits through the same passage in case of the lung (i.e. through the windpipe), but in the case of the bellows, air enters through a flap valve in the rear and is pushed out through the nozzle in the front.

Although Aristotle has described the larger mechanism of the lung, he also describes its more minute anatomy as well. The organ itself contains multiple passageways. We now call them bronchioles, but Aristotle refers to them simply as 'tubes' [σύριγγες]; it is into these tubes that the external air enters:

---

proposes that death can be caused by the *excess* of heat, since it burns up the available fuel and extinguishes itself; cf. Arist. *Resp.* 479a7-15 and 479a21-28, where death is defined as a failure of heat; cf. Harris 1973: 167-172.

διὰ τί δὲ τὰ ἔχοντα δέχεται τὸν ἀέρα καὶ ἀναπνέουσι, καὶ μάλιστ' αὐτῶν ὅσα ἔχουσιν ἔναιμον, αἴτιον τοῦ μὲν ἀναπνεῖν ὁ πνεύμων σομφὸς ὢν καὶ συρίγγων πλήρης. καὶ ἐναιμότατον δὴ μάλιστα τοῦτο τὸ μόριον τῶν καλουμένων σπλάγχνων. ὅσα δὴ ἔχει ἔναιμον αὐτό, ταχείας μὲν δεῖται τῆς καταψύξεως διὰ τὸ μικρὰν εἶναι τὴν ῥοπὴν τοῦ ψυχικοῦ πυρός, εἴσω δ' εἰσιέναι διὰ παντὸς διὰ τὸ πλῆθος τοῦ αἵματος καὶ τῆς θερμότητος. ταῦτα δ' ἀμφότερα ὁ μὲν ἀὴρ δύναται ῥᾳδίως ποιεῖν· διὰ γὰρ τὸ λεπτὴν ἔχειν τὴν φύσιν διὰ παντός τε καὶ ταχέως διαδυόμενος διαψύχει·

But why do those animals that have [lungs] receive the air and breathe, and especially those that have a blooded lung?—the cause of breathing is that the lung is spongy and full of tubes. And this contains by far the most blood of any of the so-called viscera. All animals that have a blooded lung need fast-acting cooling because the balance of the life-fire is small, and they also need it to enter through the entire lung because of the amount of blood and heat. Air is able to do both these things easily. For because it has a thin nature, it slips through the entire lung and cools it (Arist. *Resp*. 478a11-20).[116]

With this simple analogy, he explains how the lungs expand and take air into their σύριγγες, which run through the organs and are surrounded by blood.[117] The air in these tubes absorbs heat, and when the lungs collapse, the air carries this heat back into the atmosphere, thus cooling the body.[118] In general, then, even while Aristotle connects respiration to larger physiological systems involving heat transfer and digestion, his heuristic for understanding the mechanism of respiration itself involves bellows and pressurized tubes. This pressurized system does not extend throughout the entire body, however; just as for Plato, it involves only the *exchange* of internal and external air, not the general *distribution* of air.

[116] Cf. Pl. *Tim.* 70c1-d6, which describes the lung as being spongy and perforated with cavities.

[117] Arist. *Resp*. 474a12-18.

[118] Arist. *Resp*. 480a16-b20.

As for blood-distribution, Aristotle considers the heart to be the source [ἀρχή] of both blood and the blood vessels.[119] By 'source,' Aristotle does not only mean that the vessels begin in this organ, but that the heart also functions as both the purpose or 'principle,' for which the whole system is designed, and produces the blood, which it manufactures by receiving the nourishing liquid from the stomach and concocting it further.[120] Aristotle presents a somewhat confounding description of the anatomy of heart itself, stating that larger animals (such as humans) have a three-chambered heart, while smaller animals possess only a double- or single-chambered organ. In large mammals, the largest cavity sits on the right, the smallest on the left and the middle cavity in between them.[121] The largest chamber holds the hottest blood, while the smallest contains the coldest. While these have connections to the vascular system more generally, Aristotle also describes their attachment to the lungs and its σύριγγες:

> καί εἰσιν εἰς τὸν πλεύμονα τετρημέναι πᾶσαι. [ἀμφοτέρας δ' ἔχει τὰς δύο μικράς, καὶ τὸν πλεύμονα τετρημένας πάσας]. κατάδηλον δὲ κατὰ μίαν τῶν κοιλιῶν. κάτωθεν δ' ἐκ τῆς προσφύσεως· κατὰ μὲν τὴν μεγίστην κοιλίαν ἐξήρτηται τῇ μεγάλῃ φλεβί, πρὸς ἣν καὶ τὸ μεσεντέριόν ἐστι, κατὰ δὲ τὴν μέσην τῇ ἀορτῇ.
>
> All of them are stretched into the lung. [And this holds for the two small ones and all are extended to the lung]. This is quite clear in the case of one of the cavities. From below the outgrowth, in the case of the largest cavity, it is connected to the 'Great vessel' (against which is the mesentery), and

[119] Arist. *Part. an.* 666a32-34; 666b24-26. The Aristotelian model of blood flow and respiration is quite complex. It incorporates two kinds of blood (one hotter and one colder) and various pathways that the blood vessels travel to reach all the organs in the body. Aristotle also outlines three functions of the heart: leaping, beating and breathing [πήδησις καὶ σφυγμὸς καὶ ἀναπλοή] (*Resp.* 479b18-19), while also making it the seat of sensation; cf. *Gen. an.* 743b26-33. For a full discussion of Aristotle's model of the vascular and respiratory systems, see Harris 1973.

[120] Harris 1973: 135 notes that Aristotle provides no clear account of how the heart produces the blood, which suppies both nourishment [τροφή] for the body and acts as its constituent element.

[121] Arist. *Hist. an.* 496a4-27; cf. *Part. an.* 667a1-6. It is unclear which anatomical features correspond to these three chambers. Harris 1973: 126-133 ultimately concludes that no satisfactory answer can be discerned from the evidence (both textual and anatomical) and suggests that perhaps the mistake simply arose from Aristotle's doctrine of the mean.

> in the case of the middle vessel, it is connected to the aorta (Arist. *Hist. an.* 496a22-27).[122]

He goes on to explain these connections to the lung more fully:

> φέρουσι δὲ καὶ εἰς τὸν πλεύμονα πόροι ἀπὸ τῆς καρδίας, καὶ σχίζονται τὸν αὐτὸν τρόπον ὅνπερ ἡ ἀρτηρία, κατὰ πάντα τὸν πλεύμονα παρακολουθοῦντες τοῖς ἀπὸ τῆς ἀρτηρίας. ἐπάνω δ' εἰσὶν οἱ ἀπὸ τῆς καρδίας· πόρος δ' οὐδείς ἐστι κοινός, ἀλλὰ διὰ τὴν σύναψιν δέχονται τὸ πνεῦμα καὶ τῇ καρδίᾳ διαπέμπουσιν· φέρει γὰρ ὁ μὲν εἰς τὸ δεξιὸν κοῖλον τῶν πόρων, ὁ δ' εἰς τὸ ἀριστερόν.
>
> Passages continue into the lung from the heart, and they divide in the same place, just as the windpipe, and accompany those vessels from the windpipe all through the lung. And those from the heart are on top. But they do not share a common passageway, but through their synapse they receive *pneuma* and send it through to the heart; for one of the passageways goes to the right cavity, the other to the left (Arist. *Hist. an.* 496a27-33).[123]

Aristotle is proposing that vessels run from the largest cavity of the heart to the pulmonary artery, and from the smallest cavity to the aorta. It is not entirely clear precisely what Aristotle means by 'synapse' [σύναψις], since this term could indicate simply contact, or an actual junction-like perforation. In any case, it is clear that *pneuma* moves from the set of vessels extending from the windpipe, through the synapse to the heart *via* this second set of passageways (perhaps to be understood as the pulmonary veins). In fact, in *Historia animalium*, Aristotle declares that if you blow down the windpipe of an animal you are dissecting, you will inflate the heart.[124] In sum, respiration involves air moving through tubes based on mutual displacement and vacuum pressure—right up until and into the actual chambers of the heart.

---

[122] Cf. Arist. *Resp.* 478a26-28. At *De somn.* 458a15-19, Aristotle presents a somewhat different picture of the heart, insofar as he claims that the left ventricle is connected to the aorta, not the middle cavity; cf. Platt 1921.

[123] Cf. Arist. *Part. an.* 668b33-669b13 for another discussion and description of the lung.

[124] Arist. *Hist. an.* 495b14.

Once the *pneuma* reaches the heart, however, Aristotle establishes a different heuristic. That is, although he explains how air is drawn into the body by employing a bellows analogy, at the end of its tubes, the air is simply dumped out into the heart as though the organ were a non-pressurized vessel, now containing both blood and *pneuma*. At this point, he wishes to explain the pulse, and in order to do so, he utilizes another technological analogy, this time a simple comparison to a boiling pot:

> ἔστι δ’ ὅμοιον ζέσει τοῦτο τὸ πάθος· ἡ γὰρ ζέσις γίνεται πνευματουμένου τοῦ ὑγροῦ ὑπὸ τοῦ θερμοῦ· αἴρεται γὰρ διὰ τὸ πλείω γίνεσθαι τὸν ὄγκον…τῇ δὲ ζέσει ἡ ἔκπτωσις διὰ τῶν ὁριζόντων. ἐν δὲ τῇ καρδίᾳ ἡ τοῦ ἀεὶ προσιόντος ἐκ τῆς τροφῆς ὑγροῦ διὰ τῆς θερμότητος ὄγκωσις ποιεῖ σφυγμόν, αἰρομένη πρὸς τὸν ἔσχατον χιτῶνα τῆς καρδίας. καὶ τοῦτ’ ἀεὶ γίνεται συνεχῶς· ἐπιρρεῖ γὰρ ἀεὶ τὸ ὑγρὸν συνεχῶς, ἐξ οὗ γίνεται ἡ τοῦ αἵματος φύσις. πρῶτον γὰρ ἐν τῇ καρδίᾳ δημιουργεῖται.
>
> [The beating of the heart] is like boiling; for boiling happens when liquid is turned into air by heat; the liquid increases in size because its bulk gets larger…in boiling there is an overflow of the container, but in the heart the liquid flowing in from nourishment expands because of the heat and causes pulsing whenever the expansion increases to the furthest membrane of the heart. For liquid is always flowing in continuously, from which the nature of the blood is generated. For blood is crafted in the heart first (Arist. *Resp.* 479b30-480a8).

The idea is that as the blood in the heart is heated, the “moisture becomes pneumatized” [πνευματουμένου τοῦ ὑγροῦ] and begins to expand.[125] When it reaches the outer membrane, the expanding air strikes against the ‘lid’ of the heart, so to speak, and causes a beat. His use of the boiling pot analogue is quite ingenious, insofar as it incorporates the dominant feature of the heart—heat—into the process of its own functioning. Moreover, it also explains why you can feel a pulse, a feature that had heretofore been absent in accounts of blood flow. Most importantly, however, it adopts a cooking technology—however basic—to explain the operation of an organ responsible for concocting the

[125] [Hippocr.] *Vent.* also contains the notion that the blood gives off vapour.

inflowing blood. In other words, it provides another instance where Aristotle looks to a parallel technology to conceptualize a certain physiological feature—a technology to which anatomy must then conform in order for the explanation to function.

The analogy nevertheless occludes the fact that Aristotle has just described an open tube full of air running into the heart. Why does the expanding air not simply re-enter that tube? Would that cause a beat as well? He provides no mechanism to prevent this, especially since the heart valves were not discovered until a few generations later.[126] Rather, his analogy provides a complete heuristic with which to think about the phenomenon, thereby focusing attention on the expansion of liquid within a contained vessel and away from any anatomical features that prove difficult for his immediate explanatory goals. This is not to say that Aristotle could *not* provide an *ad hoc* explanation to account for this difficulty; simply that his heuristic establishes a certain cognitive frame that directs attention towards an actual pot and away from the messy anatomy of the body.

This becomes clearer when Aristotle needs to discuss a different aspect of the heart and utilizes a different and conflicting technological analogue. While the boiling-pot analogy serves Aristotle's explanation of the pulse, it does not explain how the heart expands, which he has mentioned in the *Historia animalium*. In fact, it is the very fact that a pot does *not* expand that seems to allow for the expanding air to strike against its outermost membrane and cause a pulse. In a section shortly after the above quotation,

---

[126] See section 2.1 below.

however, Aristotle adopts yet another technological analogue, returning to the analogy of the bellows once again, albeit now to describe the heart:[127]

> ἡ δ’ ἀναπνοὴ γίνεται αὐξανομένου τοῦ θερμοῦ ἐν ᾧ ἡ ἀρχὴ ἡ θρεπτική. καθάπερ γὰρ καὶ τἆλλα δεῖται τροφῆς, κἀκεῖνο, καὶ τῶν ἄλλων μᾶλλον· καὶ γὰρ τοῖς ἄλλοις ἐκεῖνο τῆς τροφῆς αἴτιόν ἐστιν. ἀνάγκη δὴ πλέον γινόμενον αἴρειν τὸ ὄργανον. δεῖ δ’ ὑπολαβεῖν τὴν σύστασιν τοῦ ὀργάνου παραπλησίαν μὲν εἶναι ταῖς φύσαις ταῖς ἐν τοῖς χαλκείοις (οὐ πόρρω γὰρ οὔθ’ ὁ πνεύμων οὔθ’ ἡ καρδία τοῦ προσδέξασθαι σχῆμα τοιοῦτον), διπλοῦν δ’ εἶναι τὸ τοιοῦτον· δεῖ γὰρ ἐν τῷ μέσῳ τὸ θρεπτικὸν εἶναι τῆς ψυκτικῆς δυνάμεως. αἴρεται μὲν οὖν πλεῖον γενόμενον, αἰρομένου δ’ ἀναγκαῖον αἴρεσθαι καὶ τὸ περιέχον αὐτὸ μόριον.
>
> Respiration happens when the heat increases, in which the nutritive principle exists. For just as the other parts also need food, so to does this part (i.e. the heart) and even more than the rest; for this is the cause of nourishment for the other parts. Indeed, as it increases, it compels the organ to rise. It is necessary to understand the structure of the organ as similar to the bellows in forges (for the lung and heart are not far from taking on such a shape), but such an organ is also double. For it must have the nutritive part of the capacity for life in the middle. And so as the heat increases, it expands, and as it expands, the part encompassing it must also expand (Arist. *Resp.* 480a16-b20).

When Aristotle wishes to address the capacity of the heart to expand, he returns to the bellows,[128] and this comparison allows him to make a new argument, despite the fact that it sits in tension with his previous analogy to a rigid cooking vessel.

At this point, then, he has described the heart using two technological analogues—the pot and the bellows—both of which operate ‘pneumatically,’ and he has constructed a model of air intake that casts certain vessels of the body as pressurized

---

[127] Arist. *Resp*. 480a23-24.

[128] Von Staden 1989: 260 presents a different interpretation. He suggests that the heart expands because of its innate heat, which causes the lung surrounding it to expand as well, thus drawing in air; this air receives some of this excess heat and the expansion of both the lungs and heart subside. While this would provide a potential mechanism of expansion and contraction in the lung, which would otherwise be left unexplained, it does not explain how the expanding, pneumatized air causes a *beat*. More importantly, however, if the heart and lung function in tandem, it suggests that our heart only beats at the same tempo as we breathe—which is an idea I have a hard time accepting Aristotle to be proposing.

tubes [σύριγγες].[129] He has even connected these two systems *via* the pulmonary vessels reaching from the lungs to the heart. Yet, the surprising feature of his account—especially for a modern reader familiar with steam generators and pumps—is that Aristotle incorporates neither the bellows nor the boiling pot as mechanisms of propulsion.[130] Instead, when Aristotle describes how blood travels around the body in *De partibus animalium*, he returns to the familiar comparison of irrigation technology. Once again, the blood flows through the body by gravity-flow, neither pushed from behind, nor driven forward:

> ἔοικε δ' ὥσπερ ἔν τε τοῖς κήποις αἱ ὑδραγωγίαι κατασκευάζονται ἀπὸ μιᾶς ἀρχῆς καὶ πηγῆς εἰς πολλοὺς ὀχετοὺς καὶ ἄλλους ἀεὶ πρὸς τὸ πάντῃ μεταδιδόναι, καὶ ἐν ταῖς οἰκοδομίαις παρὰ πᾶσαν τὴν τῶν θεμελίων ὑπογραφὴν λίθοι παραβέβληνται διὰ τὸ τὰ μὲν κηπευόμενα φύεσθαι ἐκ τοῦ ὕδατος, τοὺς δὲ θεμελίους ἐκ τῶν λίθων οἰκοδομεῖσθαι, τὸν αὐτὸν τρόπον καὶ ἡ φύσις τὸ αἷμα διὰ παντὸς ὠχέτευκε τοῦ σώματος, ἐπειδὴ παντὸς ὕλη πέφυκε τοῦτο. γίνεται δὲ κατάδηλον ἐν τοῖς μάλιστα καταλελεπτυσμένοις οὐθὲν γὰρ ἄλλο φαίνεται παρὰ τὰς φλέβας, καθάπερ ἐπὶ τῶν ἀμπελίνων τε καὶ συκίνων φύλλων καὶ ὅσ' ἄλλα τοιαῦτα· καὶ γὰρ τούτων αὐαινομένων φλέβες λείπονται μόνον. τούτων δ' αἴτιον ὅτι τὸ αἷμα καὶ τὸ ἀνάλογον τούτῳ δυνάμει σῶμα καὶ σὰρξ ἢ τὸ ἀνάλογόν ἐστιν· καθάπερ οὖν ἐν ταῖς ὀχετείαις αἱ μέγισται τῶν τάφρων διαμένουσιν, αἱ δ᾽ἐλάχισται πρῶται καὶ ταχέως ὑπὸ τῆς ἰλύος ἀφανίζονται, πάλιν δ' ἐκλειπούσης φανεραὶ γίνονται, τὸν αὐτὸν τρόπον καὶ τῶν φλεβῶν αἱ μὲν μέγισται διαμένουσιν, αἱ δ' ἐλάχισται γίνονται σάρκες ἐνεργείᾳ, δυνάμει δ' εἰσὶν οὐδὲν ἧσσον φλέβες. διὸ καὶ σῳζομένων τῶν σαρκῶν καθ' ὁτιοῦν αἷμα ῥεῖ διαιρουμένων· καίτοι ἄνευ μὲν φλεβὸς οὐκ ἔστιν αἷμα, φλέβιον δ' οὐδὲν δῆλον, ὥσπερ οὐδ' ἐν τοῖς ὀχετοῖς αἱ τάφροι πρὶν ἢ τὴν ἰλὺν ἐξαιρεθῆναι.
>
> [The systems of vessels] are similar to irrigation systems that are built in gardens to transmit [water] everywhere, [leading it] from one source and spring into numerous other channels; and just like in building, when stones are set along the entire outline of the foundation, nature has also channeled

[129] Arist. *Cael.* 305a33-b26 also recognizes the potential force of steam, since here Aristotle acknowledges that a sealed vessel with water in it will explode because of the expanding vapour.

[130] Cf. [Hippocr.] *De flat.* 8.18-40, where the boiling pot analogue explains how fevers heat the body's air, which forces open the jaw.

> blood through the whole body in the same way, since this is the constituent matter of it all. This is clear in people who are especially thin. For in these cases, nothing other than the blood vessels are visible, just as in vines and fig leaves and all other such things—for when these things wither, their veins alone remain. The cause of this is that the blood (and its analogue) is potentially the body and the flesh (or its analogue). And so, just as in channels, the biggest of the trenches persist, while the smallest disappear first and fastest under a coat of muck, only to reappear again when the muck recedes; in the same way the biggest veins persist, while the smallest become flesh in actuality, but potentially they are nothing less than veins. For this reason, whenever the flesh is healthy, blood will flow wherever the flesh is cut. However, without veins there is no blood, even if the smallest vein is not actually visible, just as in the channels the trenches are not visible until the mud has been cleared (Arist. *Part. an.* 668a11-32).

Aristotle moves from σύριγγες, functioning pneumatically in the lungs and heart, to spring-fed ὀχετοί, functioning through gravity-flow in the blood vessels. Instead of employing models of propulsion in the above passage, Aristotle leaves the flow of blood basically unexplained, allowing the analogue of irrigation to do most of the work for him. He even allows this comparison to dictate other aspects of physiology, including hypothetical veins that cannot actually been seen because they are too small and only appear once the 'muck' of the flesh recedes. That is, the technological comparison of irrigation leads him to posit entities that he can truly only observe by inference.

Aristotle thus uses three separate sets of analogues, which establish multiple heuristics: he uses a pot-analogy to explain how concocted blood causes a pulse, but includes a conflicting bellows-analogy to account for the heart's expansion; he incorporates the pneumatic action of vessels as σύριγγες in respiration, while using a non-pressurized view of the vessels as ὀχετοί in blood-delivery. When he needs to think about air transfer, he adopts air transfer technologies as conceptual tools; when he needs to think about blood-delivery, he thinks with water delivery technologies. The fact that these two implements work in different ways in fourth century BCE Athens leads to different localized assumptions about human physiology. He interprets the individual structures of the body according to the cognitive tools at hand. Thus, although he is not simply bound by them, technologies structure his physiological ideas, allowing him to hold two conflicting views of the heart and two different views of the blood vessels, while he presents ideas that mirror his technological environment.

1.4 Conclusion

What does it mean for Aristotle and his predecessors to use these technologies to support or even stand in for theories in this way? At the very least, it demonstrates the powerful conceptual pull that material implements exert as a way to comprehend and structure natural phenomena. Aristotle, like his predecessors, strives to understand the opaque, closed human body. Yet, even when it is opened up and exposed to the world, its interlocked parts are hard to differentiate, and even major organs leave few clues as to their operation other than their macroscopic structural elements and their connections to other body parts. Technologies serve as ready-at-hand cognitive tools to decode these masses. As the above examples demonstrate, however, even this presents a somewhat idealist model of how theory formation works, since it presumes that the observations come first and the technological heuristics are employed to explain certain body parts. In reality, it seems that the analogues play a much larger role in predicating how authors identify structures of the body—even those that they do not see. The resulting anatomy is some hybrid of those anatomical features *interpreted* by a technological heuristic (how does blood flows *via* the veins?) and those *derived* from it (the chest is rigid like a *clepsydra*; the heart is rigid like a pot; small veins that cannot be seen transform into flesh). In fact, once these technological analogues are employed they often leave behind the actual anatomy supposedly being interrogated and become the main site of explanation. In 'thinking with' these technological analogies, authors 'think within' the heuristics that they create so that any physical discrepancies can easily be overlooked, since theorists are no longer looking directly at the body, but focusing their attention on their conceptual model.

In general, these conclusions lead us to ask how integrated even Aristotle's physical arguments are—that is, not how integrated they *could* be, since it is certainly possible to employ *ad hoc* secondary theses in each case to reintegrate any discrepancies within a larger, coherent physiological framework. Instead, we can ask how much of his encounter with the world is dictated by moving from his core principles outwards and how much is dictated in a far more localized way. In the case of the latter, his assumptions about particular experiences and natural phenomena would come first and only *then* need to be stitched into his greater philosophical framework. The fact that this question can be raised for Aristotle, one of the most systematic thinkers in antiquity, makes the question even more pressing for other ancient natural philosophers. In general, it allows for a modal understanding of theory-formation concerning the natural world, whereby arguments and analogues are deployed at specific times to suit certain needs. Many of these arguments rest on finding an appropriate technological analogue and letting it stand in as a type of theory.

Chapter Two
Pneumatics, Aqueducts and the Pressurized Body

2.0 Introduction: Alexandria and Rome

In the early third century BCE, Alexandria become the new cultural and intellectual capital of the Greek-speaking world, as thinkers from around the Mediterranean descended upon the *Mouseion* and Library established by Ptolemy I Soter. The city hosted some of the major intellectual forces of the era, including Euclid, Callimachus, Apollonius and Eratosthenes. This thriving intellectual climate led to the growth of innovation across multiple fields, including science, medicine, engineering, literature and mathematics. The era also saw significant material and technological advances, including those in water technology. To be sure, by the third century BCE large-scale water-distribution systems had not changed entirely—wells were still in use, as were cisterns,[131] and water was still being brought from springs through gravity-flow aqueduct channels; yet, infrastructure had improved: pipes were now often laid out along the grid-pattern of the streets, supplying both ornate public fountains[132] and a greater number of private houses;[133] aqueducts also became larger and longer, although they were still generally constructed of pipes and not the masonry conduits that became popular in the Roman period.[134] The increasing complexity of water delivery systems may have also led to water supervision and regulation being placed under the control of

[131] Hodge 2000: 21-33.

[132] A third century BCE papyrus references a fountain at Alexandria with a semi-circular base and three statues, one of which depicted Arsinoë; cf. Glaser 2000a: 437-438.

[133] Constructing water features in private gardens is first seen in the Hellenistic period; cf. Glaser 2000b.

[134] Hodge 2002: 31-33, 2000: 42-43; Jansen 2000: 109; Wilson 2008: 294-296.

specialized magistrates, who would have dealt with the new legal complications that arose.[135] While these enhancements represent expansions of previously existing implements rather than completely new inventions, a few innovations of the period did affect theories of respiration and the vascular system: the increasing use of the inverted siphon, the rise of pneumatic devices and the invention of the force pump.[136]

Several scholars have suggested that the development of pneumatic mechanisms in the early third century BCE led to a parallel shift in thinking about the body in these same terms. Devices that functioned by means of water pressure were now available both as material implements and—by extension—cognitive tools. In particular, Erasistratus of Ceos not only proposed a general pneumatic framework to understand human physiology, but also adopted the newly invented force pump as a model to understand the heart, viewing this organ as a mechanism of propulsion for the first time. Through the first half of this chapter, I will thus illustrate how Erasistratus reads pneumatic technologies into the structures of the body and interprets observed features according to the parameters set by his contemporary machines. Moreover, I will also show how his etiology of disease reflects a conceptual reliance on pneumatic devices. In other words, I will articulate how technological innovation led to conceptual innovation. In the second part of this chapter, however, I will argue that any narrative of correlated material invention and conceptual advancement implicitly structures the relationship between technology and theory as a linear progression of discovery, whereby improved tools lead to improved ideas about the body. Theory-formation, however, works in a far less linear fashion.

---

[135] For a general overview of water technology in the Hellenistic period, including these advancements, see M. Lewis 2000b: 640-641.

[136] For an overview of inverted siphons in this period as well as aqueduct technology, see Hodge 2002: 31-45.

Cognitive worlds are not made up of the latest advances alone. Instead, as I illustrated in the last chapter, heuristics can operate modally even for the same thinker. Within the greater history of ideas, then, we should not be surprised to see that technologies do not always supply a succession of ever-improving conceptual tools, but function in more localized and fragmented ways. Newer and potentially more sophisticated implements may not always prove the most powerful or enticing, and just because a new technology is invented (e.g., an mp3 player), an older technology may still be used in analogical heuristics (e.g., a record player)—especially if those older technologies are still in use. Within the history the vascular system, for instance, pneumatic devices are dazzling; yet, the cultural significance of the aqueducts in Rome seem to have made the latter more consequential for the construction and reception of the physiological ideas of Asclepiades of Bithynia in the late second and early first century BCE.[137] This chapter will therefore first articulate how shifts in technology can produce corresponding shifts in scientific conceptions, only to then illustrate how these changes should not be understood as simple steps in the inevitable advancement of both technological and scientific discovery, but instead as a potentially expanding set of cognitive tools being used to construct different edifices to suit localized purposes.

2.1 The Pump and the Pressurization of the Body

As part of the flourishing intellectual culture of the Hellenistic era, craftsmen turned their attention to constructing devices designed to promote wonder and amazement. Those by Ctesibius of Alexandria (290-250 BCE) and Philo of Byzantium

[137] Given the remarkable engineering required to construct them, one could also easily argue that Roman aqueducts, while operating on the same gravity-flow model as earlier irrigation channels, were far more sophisticated than small pneumatic devices.

(ca. 240–ca. 200 BCE) included pneumatic *automata*, birds that drank water, steam-driven temple doors, a musical horn of plenty, a water organ[138] and a water clock with automated moving parts.[139] These machines sometimes incorporated valves to ensure unidirectional flow of water, employed siphon mechanisms to drink and dispense liquid and harnessed pneumatic pressure to make music. Vitruvius marvels at these devices and takes pains to describe their wonderous features:

> *…etiam plures et variis generibus ab eo liquore pressionibus coactae spiritus efferre ab natura mutuatos effectus ostendentur, uti merularum aquae motu voces atque angubatae, bibentiaque et eadem moventia sigilla ceteraque, quae delectationibus oculorum et aurium usu sensus eblaniantur.*
>
> There are many others of various kinds that are driven by the pressure of water. *The pneumatic pressure will be shown to produce effects borrowed from nature,* both notes of blackbirds by the motion of water, and walking *automata*; little figures which drink and move and other things which flatter the pleasure of the eyes and the use of the ears (Vitr. *De arch.* 10.7.4).

These dazzling machines would have utilized watertight vessels and pipes and would not only have functioned while under pressure, but also by virtue of it. Perhaps more intriguingly, a number of these devices mimicked the movements of animals, as craftsmen attempted to re-create the natural world through human ingenuity. Vitruvius claims these technologies "put on display" [*ostendentur*] natural effects, and "borrowed from nature" [*ab natura mutuatos*]. In the next section, however, we will see the thin line dividing 'exhibit,' 'represent,' 'demonstrate' and 'embody,' as pneumatic machines designed to *mimic* nature end up standing in for the mechanisms of nature themselves.

---

[138] See Vitr. *De arch.* 10.8 for a description.

[139] Most of these can be found in Philo, *Pneum.*, Hero, *Pneum.* and Vitr. *De arch.* 10.7.4-5. For an investigation of the hydraulic inventions of this period, see M. Lewis 2000a; 343-369; for a general survey of technology in this period, see Sarton 1959: 117-128, 343-378; Wilson 2008: 337-366.

While these more spectacular implements would have made quite an impression, basic water infrastructure of the period also improved, growing in both size and complexity. Inevitably, these longer water supply systems needed to flow across valleys and other uneven terrain, and in order to do so they integrated inverted siphons.[140] These function when the source on one side of the valley is higher than its delivery point on the other. As long as the water's entry point remains above its exit point on the other side, the inflowing water will run downwards and push the water ahead of it up the incline—that is, as long as the pipe is closed and able to run at pressure.[141] In other words, delivery systems now increasingly incorporated sections that ran with water alone—or, to use our earlier terms, included more σύριγγες that functioned as ὀχετοί.

Despite the increased complexity of these technologies, none of them truly relies on any newly discovered physical principles, since they more or less redeploy already known physical behaviours of mutual displacement, gravity-flow and vacuum pressure, albeit in new and sophisticated ways. To be sure, new philosophical ideas about the nature of the void emerged during this period, including the concept of the micro-void,[142] but it is hard to discern whether these new ideas *led* to an interest in pneumatic mechanisms or *resulted* from them—or, as is more likely, whether there was some

---

[140] Hodge 2002: 33-45, 2000: 42-46. Wilson 2008: 295-296; cf. Ortloff 2009: 278-295 for technical details. There is one small inverted siphon at Olynthus, which Crouch 1993: 171-174 dates to the late sixth century or early fifth BCE, while Lewis 1999: 157, n. 9 dates it somewhere between the sixth and fourth centuries BCE. In the East alone inverted siphons dating to the very early Roman period have been found at Magnesia ad Sipylum, Philadephia, Antioch on the Meander, Blaundos, Patara, Smyrna, Prymnessos, Tralleis, Trapezopolis, Antioch in Pisidia, Apamea Kibotos, Akmonia, Laodicea and, most importantly, Pergamon; cf. Hodge 2002: 33.

[141] M. Lewis 2000b: 646-647 states that the pressure in inverted siphons can reach as high as approximately 240 lb/in^2 or 18.5 kg/cm^2, equal to that which is exerted in the boilers of a steam engine. Vitruvius was obviously aware of the extreme pressures at work in these devices, since at *De arch.* 8.6.8-9 he insists that pipes under these conditions need to be substantially reinforced.

[142] See n. 153 below.

interplay between the two. In any case, abstract principles were bound to and embodied within material technologies. It was not a disembodied, abstract concept of *horror vacui* that affected the way these principles were used to understand human physiology, but the specific devices developed by Hellenistic inventors. In fact, the increase in pneumatic and pressurized technology seems to have had its effect on one Hellenistic medical theorist in particular, Erasistratus of Ceos, who provides a prime example of someone who deployed his abstract concepts in relation to his technological environment.

In the early third century BCE, Erasistratus and his predecessor Herophilus of Chalcedon conducted systematic dissections in Alexandria, making great leaps forward in anatomical knowledge.[143] Their discoveries came no doubt as a result of dissecting humans (rather than animals alone), which previous religious and cultural prohibition seems to have prevented.[144] As part of these discoveries, Herophilus identified an entirely new set of vessels in the body—the nerves—which he differentiated into two types: motor [προαιρετικά] and sensory [αἰσθητικά].[145] He distinguished the ventricles of the

---

[143] Herophilus was born in Chalcedon between 330-320 BCE and immigrated to Alexandria some time after 315 BCE. Some scholars have him studying in Athens first, which would push back his arrival in Alexandria by some years, perhaps into the early third century. For a full account of Herophilus' life, see von Staden 1989: 35-66. Although Fraser 1969 argues that Erasistratus did not practice in Alexandria, but conducted his medical research in Antioch, both Harris 1973: 177-233 and Lloyd 1975 have rebutted this claim; cf. Longrigg 1988: 472-473. Erasistratus likely practiced in Alexandria during the first half of the third century BCE, at the same time as Herophilus. That places him as an older contemporary to Ctesibius, who lived and worked under the reigns of Ptolemy I and II at the *Mouseion*. Nevertheless, we ought to be weary of assuming that Herophilus and Erasistratus researched at the *Mouseion* under the financial support of the Ptolemies; cf. Von Staden 1989: 26-31, 1992; Vegetti 1995.

[144] Various suggestions have been made to explain this development, including Plato's and Aristotle's secularization of the corpse and the influence of Egyptian mummification practices; cf. Sarton 1959: 129-130; Longrigg 1988: 45; von Staden 1996: 85-86; Nutton 2004: 128-139. To understand how far Herophilus and Erasistratus broke from cultural norms, we can consider that Cels. *Med.* 1. *proem.* 23-26 charges them with practicing vivisection on condemned criminals, although this claim is debated.

[145] Ruf. Eph. *De anat. part. hom.* 71-5 = Heroph. T 81 von Staden. For a full discussion of the discovery of the nerves and how Herophilus thought them to function, see Solmsen 1961 184-197; cf. von Staden 1989: 247-259. There is, however, debate as to whether the nerves all carried *pneuma*, or only certain sets of

brain and discerned four different membranes of the eye—which makes him responsible for naming both the *cornea* [κερατοειδής] and the *retina* [ἀμφιβληστροειδής].[146] What is more important for our purposes, however, is that he separated the blood vessels into two anatomical types: arteries and veins, noting that arteries have a thick covering,[147] whereas veins do not.[148] He also proposed that only the veins contain blood alone, while the arteries transfer both *pneuma* and blood.[149]

Despite these anatomical discoveries, his model of respiration seems to reflect the same type of division that we saw with Aristotle: he discusses the *intake* of *pneuma* as pressurized, but explains its *distribution* on the model of flow. After all, Herophilus belonged to a generation of thinkers before Ctesibius and the rise of pneumatic mechanisms. Yet, unlike Aristotle, he suggests that the process of respiration involves

---

them; cf. von Staden 1989: 241-259. Harris 1973: 231-232 questions the degree to which Herophilus truly separated out these new 'nerves' from νεῦρα (ligaments).

[146] In addition, Herophilus offered the first accurate description of the liver as well as discovering the ovaries and fallopian tubes. Moreover, in his examination of the female reproductive organs, he also rejected the possibility of a bicameral womb, with a hot and cold chamber for boys and girls respectively. In addition, he demonstrated the anatomical impossibility of the wandering womb. For a full catalogue of Herophilus' discoveries, see Longrigg 1988: 462-471; von Staden 1996.

[147] Cf. Gal. *De usu part.* 6.10 K. 3.444-446; Heroph. T 116 von Staden.

[148] Gal. *De diff. pulsum* 4.10 K. 8.747.

[149] *Anon. Lond.* 28.47-49. Herophilus' predecessor and teacher, Praxagoras of Cos, seems to have made a similar distinction, but his argument was physiological (veins contained blood and arteries contained air), not anatomical; cf. Longrigg 1988: 467; von Staden 1989: 173. It is the anatomical distinction that leads to a difference in behaviour: the thin veins *collapse* when emptied of blood, whereas the thick arteries do not; cf. Gal. *De diff. pulsum* 4.10 K. 8.747. Moreover, Herophilus also correctly identified that only arteries carry a pulse and proposed an intricate system that attributed pathological significance in its different rhythms. Herophilus interprets the pulse with musical terminology apparently derived from Aristoxenus of Tarentum, the primary *differentiae* of pulse types being rhythm, speed, size and vehemence or strength. In fact, different ages of life should have different pulse types based on different poetic meters. Healthy youths should display a pyrrhic pulse rhythm (- -); adolescents should have to a trochaic pulse (— -), grown men a spondaic pulse (— —) and old men an iambic (- —). Patients could display *heterorythmia*, when the pulse does not match their age, or *ekrhythmia* if no characterizable pulse can be discerned. This is an instance where new phenomena are being interpreted based on a comparison to an extant 'technology,' albeit a poetic technique rather than a material tool. See von Staden 1989 for a full discussion of this pulse-lore.

four ‘movements’ and ultimately serves to replenish psychic *pneuma*, not to regulate heat. Herophilus is one of the few thinkers who does not connect respiration to the heart, and instead simply describes how *pneuma* enters the thorax.[150] To judge from doxographical reports, he seems to suggest that the lung alone has the natural capacity to dilate and contract and that by expanding, it first draws in external air [ἐφέλκεται]. Second, the thorax “channels” *pneuma* into itself [μετοχετεύει]. Third, when the thorax is full and unable to receive any more air, the excess “flows back” [ἀντιμεταρρεῖ] into the lung, which then, as a fourth motion, contracts and expels the air:

> ὅτε μὲν γὰρ διαστολή, < ὅτε δὲ συστολή, > γίνεται πνεύμονος, ταῖς ἀλλήλων ἀντιμεταλήψεσι πληρώσεώς τε καὶ κενώσεως γινομένης, ὡς τέσσαρας μὲν γίνεσθαι κινήσεις περὶ τὸν πλεύμονα, τὴν μὲν πρώτην καθ᾿ ἣν ἔξωθεν ἀέρα δέχεται, τὴν δὲ δευτέραν καθ᾿ ἣν τοῦθ᾿ ὅπερ ἐδέξατο θύραθεν ἐντὸς αὑτοῦ πρὸς τὸν θώρακα μεταρρεῖ, τὴν δὲ τρίτην καθ᾿ ἣν τὸ ἀπὸ τοῦ θώρακος συστελλόμενον αὖθις εἰς αὑτὸν ἐκδέχεται, τὴν δὲ τετάρτην καθ᾿ ἣν τὸ ἐξ ὑποστροφῆς ἐν αὐτῷ γινόμενον θύραζε ἐξερᾷ. τούτων δὲ τῶν κινήσεων δύο μὲν εἶναι διαστολάς, τήν τ᾿ ἔξωθεν τήν τ᾿ ἀπὸ τοῦ θώρακος· δύο δὲ συστολάς, τὴν μὲν ὅταν ὁ θώραξ ἐφ᾿αὑτὸν τὸ πνευματικὸν ἑλκύσῃ, τὴν δ᾿ ὅταν αὐτὸς εἰς τὸν ἐκτὸς ἀέρα ἀποκρίνῃ· δύο γὰρ μόναι γίνονται περὶ τὸν θώρακα, διαστολὴ μὲν ὅταν ἀπὸ τοῦ πνεύμονος ἐφέλκηται, συστολὴ δ᾿ ὅταν τούτῳ πάλιν ἀνταποδιδῷ.
>
> Sometimes dilation, and other times contraction of the lung occurs, since repletion and evacuation occur by mutual exchange with one another, so that four motions occur in the lung: the first when it receives the air from outside; the second when that which it has received externally flows in turn to the thorax inside; the third when that which is contracted from the thorax is again received back into it; and the fourth when it expels to the outside that which has arrived in it from the reverse movement. Two of these motions are dilations (i.e. the one from outside and the one from the thorax), and two are contractions (i.e. the motion when the thorax draws the pneumatic substance into itself, and when the lung itself separates [this substance] into the external air). For two [motions] alone concern the thorax: dilation, whenever it draws air into itself from the lung, and

[150] For discussions of those who connect respiration and the vascular systems, see Wellman 1901: 82-85, 71, 100; Rüsche 1930: 115-126, 208-239; Furley and Wilkie 1984: 3-39; von Staden 1989: 239.

> contraction, whenever it returns it back again to the lung (Aët. 4.22.3 = [Plut.] *Plac.* 4.22 = Heroph. T 143b von Staden).[151]

On the one hand, by classifying the movements of the thorax as "dilation" and "contraction," Herophilus proposes a mechanism of respiration that functions like a pressurized, four-stroke exchange engine. On the other hand, if the vocabulary above reflects Herophilus' own terms, the older conceptual division between two different types of physiological systems remains, insofar as *pneuma* is drawn into the body *via* some type of vacuum pressure but merely 'channeled' to the thorax when it needs to be distributed. Thus, for all Herophilus' concern with the vascular system, it was his younger contemporary, Erasistratus, who presented a model of respiration and circulation that more closely reflected contemporaneous trends in water technology.

At first glance, Erasistratus' conception of the body seems to be most heavily influenced by the philosophical ideas of Strato,[152] whose theory of a non-continuous void is preserved in Hero's preface to the *Pneumatica*, namely, that a substance "fills up a place being emptied according to an amount correlate to the other substance" [κατὰ τοσοῦτον ἕτερον ἐπακολουθοῦν τὸν κενούμενον ἀναπληροῖ].[153] Erasistratus' physiological model relies on a similar type of pneumatic/hydraulic pressure, which he calls simply "the filling towards what is being emptied" [ἡ πρὸς τὸ κενούμενον

[151] Cf. [Galen] *De hist. phil.* 103 = Heroph. T 143c von Staden.

[152] Since as early as Diels 1893, scholars have noted the connection of Erasistratus' ideas to Strato's conception of interstitial void; cf. Harris 1973: 200-233; Longrigg 1988: 474; von Staden 1996, although Berryman 1997, 2009: 197-200 has refined some of these claims. For a discussion of Strato and his pneumatic theories, see Wehrli 1850; Gottschalk 1964a; Fraser 1972, v. 1: 427-428; Lehoux 1999.

[153] Hero, *Pneum.*1, *proem.* 339-340; cf. Simplic. *In phys.* 693, who suggests that Strato denied the possibility of a continuous or contiguous vacuum in nature, but held that smaller *vacua* can exist in little micro-voids within all bodies. Strato argues that if there were no such micro-voids, when sun-rays fall upon a glass filled to its maximum capacity, the water would overflow; cf. Hero, *Pneum*. 6, who compares the idea to grains of sand on the beach.

ἀκολουθία]. On the one hand, this principle does resemble Strato's and places Erasistratus squarely within a medico-philosophical tradition of arguments about the void. On the other hand, as I argued above, abstract principles are often embodied in material technologies, which implicitly steer the application of these principles. Thus, although we can recognize the philosophical counterparts to Hellenistic physiological theories, we should not stop at identifying the potential matrices of literary and philosophical influence. Rather, we should also examine the technological environment to see how these ideas are instantiated in their material world. Doing so reveals that Erasistratus' model of the heart does indeed bear a striking resemblance to a certain pneumatic device invented around the same time: Ctesibius' force pump.

Philo and Hero both describe Ctesibius' force pump (although they present slightly different models).[154] It is Vitruvius, however, enamored as he is with Alexandrian inventions, who takes the greatest pains to articulate its parts:

> *Insequitur nunc de Ctesibica machina, quae in altitudinem aquam educit, monstrare. Ea sit ex aere. Cuius in radicibus modioli fiunt gemelli paulum distantes, habentes fistulas furcillae figura similter cohaerentes, in medium catinum concurrentes. In quo catino fiant asses in superioribus naribus fistularum coagmentatione subtili conlocati, qui praeobturantes foramina narium non patiuntur quod spiritu in catinum est expressum…Modioli autem habent infra nares inferiores fistularum asses interpositos supra foramina eorum, quae sunt in fundis. Ita de supernis in modiolis emboli masculi torno politi et oleo subacti conclusique regulis et vectibus conmoliuntur. Qui erit aer ibi cum aqua, assibus obturantibus foramina cogent. Extrudent inflando pressionibus per fistularum nares aquam in catinum, e quo recipiens paenula spiritu exprimit per fistulam in altitudinem, et ita ex inferiore loco castello conlocato ad saliendum aqua subministratur.*
>
> Now, we turn to describe the Ctesibian machine, which raises water to a height. Let it be made of bronze. At its base let there be twin cylinders, a

[154] See Philo, *Pneum. appendix* 1.2 = 192-194 Carra de Vaux, quoted below); Hero, *Pneum.* 1.28; cf. Plin. *NH*. 7.125, who also states that Ctesibius invented the force pump, as well as other "hydraulic implements" [*hydraulica organa*], by which he likely means the water organ.

> small distance apart, with outlet pipes that join together like a fork and run into a vessel between them. In this vessel, let there be valves fit with precise joints on the top openings of the pipes. Let these valves, by closing shut, prevent the air that has been driven into the middle vessel from flowing back into the opening of the cylinders…The cylinders, however, also have valves beneath the lower openings of the pipes, placed above the lowest entry points, which sit on the bottom. Thus, pistons, having been smoothed on the lathe and rubbed with oil, are now inserted from above into the cylinders, and these pistons are set in motion by pushing and pulling rods. They thus drive forward whatever air and water is in the cylinders, since the valves close shut. By inflating they push out water through the openings of the pipes and into the middle vessel by pressure, where a cover, receiving the water, forces it through the pipe by pneumatic pressure and out into the air. And in this way, from a lower place, water is led to leap to where a reservoir has been placed (Vitr. *De arch.* 10.7.1-3).

As it is described here, the pump has two cylinders (each of which were probably oiled on the inside to ease motion and to help with a seal), and two pistons run inside them. Archaeological evidence suggests that later models joined the operation of both pistons by a single pivoting handle, but Vitruvius' seem to be driven up and down separately.[155] When the piston is drawn upwards, water is drawn in through the intake valve located on or near the pipe's bottom, while the outflow valve is pulled closed by the negative pressure. When the piston is forced downward, water presses the intake valve shut and forces the outflow valve open, through which the liquid exits.[156]

Although von Staden has provided the fullest account, it was Lonie who first suggested that this force pump might have influenced Erasistratus' conception of the

[155] For a full investigation of the force pump, including both literary descriptions and archaeological evidence, see Oleson 1984: 301-325; cf. Stein 2004 and Wilson 2008: 353-354.

[156] Oleson 1984: 306-307 argues the water was more likely pushed in by ambient pressure; however, there would have to be enough internal pressure to pull closed the outflow valve as well. Oleson also argues that the original valves were likely made of leather flaps, modeled on those of the air bellows, rather than spindle valves, which later became popular; cf. Hero, *Pneum.* 10 for a description of a flap valve.

heart,[157] since unlike Plato and Aristotle before him, Erasistratus proposed for the first time that the heart serves not only as the source of blood, but also as a mechanism of propulsion. Moreover, although Herophilus seems to have discovered the heart valves before him,[158] it was Erasistratus who first suggested that they prevent backflow in a way very similar to the above description. Galen provides the longest and most detailed account of Erasistratus' model:

> εἰσὶ δ' ἐπὶ μὲν τῷ στόματι τῆς κοίλης φλεβὸς τρεῖς ἀκίδων γλωχῖσιν ὁμοιότατοι τὴν σύνταξιν, ὅθεν οἶμαι καὶ τριγλώχινας ἔνιοι τῶν Ἐρασιστρατείων ἐκάλεσαν αὐτούς...ἐξάγει δ', ὡς Ἐρασίστρατός φησιν ἐξηγούμενος τὸ φαινόμενον, ἑκάτερον μὲν τῶν στομάτων, αἷμα μὲν εἰς τὸν πνεύμονα τὸ ἕτερον αὐτῶν, πνεῦμα δ' εἰς ὅλον τὸ ζῷον τὸ ἕτερον· ἡ χρεία δὲ τῶν ὑμένων, ὡς ἐκείνῳ δοκεῖ, πρὸς ἐναντίας ὑπηρεσίας τῇ καρδίᾳ χρόνων ἀμοιβαῖς ἐγκαίροις ὑπαλλαττομένας, τοὺς μὲν ἐπὶ τοῖς εἰσάγουσι τὰς ὕλας ἀγγείοις ἐπιπεφυκότας ἔξωθεν ἔσω φερομένους ἀνατρέπεσθαι μὲν ὑπὸ τῆς εἰσόδου τῶν ὑλῶν, ἀναπίπτοντας δ' εἰς τὰς κοιλότητας τῆς καρδίας ἀνοιγνύντας τὰ στόματα παρέχειν ἀκώλυτον τὴν φορὰν τοῖς εἰς αὐτὴν ἑλκομένοις. οὐ γὰρ δὴ αὐτομάτως γε τὰς ὕλας εἰσρεῖν φησιν ὡς εἴς ἄψυχόν τινα δεξαμενήν, ἀλλ' αὐτὴν τὴν καρδίαν διαστελλομένην ὥσπερ τὰς τῶν χαλκέων φύσας ἐπισπᾶσθαι πληροῦσαν τῇ διαστολῇ. ἐπὶ δὲ τοῖς ἐξάγουσιν ἀγγείοις τὰς ὕλας <ἄλλους> ἔλεγεν ἐπικεῖσθαι καὶ τοὐναντίον ἡγεῖσθαι πάθος πάσχειν· ἔσωθεν γὰρ ἔξω ῥέποντας ἀνατρεπομένους μὲν ὑπὸ τῶν ἐξιόντων ἀνοιγνύναι τὰ στόματα καθ' ὃν ἂν ἡ καρδία χρόνον χορηγῇ τὰς ὕλας, ἐν δὲ τῷ λοιπῷ παντὶ κλείειν ἀκριβῶς τὰ στόματα μηδὲν τῶν ἐκπεμφθέντων ἐπανέρχεσθαι συγχωροῦντας.
>
> At the mouth of the *vena cava*, there are three membranes, similar in shape to the barbs of arrows—for which reason I think some of the Erasistrateans have called them the 'tricuspids'…As Erasistratus says when he is describing the phenomenon, one of the mouths guides blood to the lungs, and the other guides *pneuma* to the whole animal. The use of these membranes in the heart, as it seems to him, is toward opposite purposes, alternating at different times. The ones attached to the vessels

[157] Lonie 1973; von Staden 1996; cf. von Staden 1997, 1998. Both Majno 1975: 332 and Vallance 1990: 70 accept the suggestion, but Longrigg 1993: 208-209 and Berryman 2009: 200 are more skeptical; Russo 2004: 147 inverts the direction of influence, suggesting that the discoveries in the heart may have led to the invention of the pump, but this seems unlikely given that the heart was not previously seen to be a mechanism of propulsion.

[158] Gal. *De plac. Hipp. et Plat.* 1.10.3-4 = Heroph. T 119 von Staden.

> leading matter from the outside and into the heart are turned around by the entrance of matter, and by falling inwards and opening towards the cavity of the heart, they provide an unhindered passage into the ventricles. For, he says that *the matter does not flow in automatically, as if a lifeless cistern were receiving it, but the heart itself, expanding like the bellows of a forge, draws it in through its dilation.* He says that there are membranes fitted to the vessels leading matter out of the heart and that they suffer the opposite movement. For he says that by turning from the inside outwards, they open the mouths of the vessels because of the matter flowing out, whenever the heart distributes matter, but for the rest of the time they close the mouths tightly and prevent any of what has been pushed out from flowing back in (Gal. *De plac. Hipp. et. Plat.* 6.6.6-12, emphasis mine).

Galen's description is easy to follow. Erasistratus proposes that there are four chambers to the heart, with two sets of intake and outflow valves, one pair on each side of the heart. No longer does blood simply flow into the vessels by its own downward inclination; rather, when the ventricles expand, they draw substances in through an intake valve, and when they contract, they push it out through their respective outflow valves. Erasistratus hereby establishes the heart as an organ of both suction and propulsion in distinction to a "lifeless cistern."[159] That is, Erasistratus sets up a dichotomy between the static, gravity-fed spring described by Plato and (to a lesser degree) by Aristotle and his vital, pneumatic heart.

Erasistratus' heart certainly involves the same hydraulic and pneumatic principles as Ctesibius' machine, and—as von Staden has suggested—Erasistratus' heart and the force pump have many similarities: both have two chambers; both are equipped with valves to ensure unidirectional flow; both have four sets of valves, two controlling intake and two regulating outflow from the two chambers; both function on 'forked pipes'

[159] Cf. [Hippocr.] *De corde* 8, which describes the heart's "ears" [τὰ οὔατα] breathing in and collapsing, and also compares the lungs to the bellows. Keyser and Irby-Massie 2008 dates this treatise *ca.* 350-250, perhaps contemporary to the discoveries of Erasistratus; cf. Jouanna 2001: 394, who dates it simply to the Hellenistic era, sometime after the discoveries of Erasistratus. I think the latter is more likely.

[*fistulae furcillae*] or vessels; both depend centrally on the principle of an intermediate valved-chamber [*medius catinus*]; both are twin-cylinder apparatuses sitting in a round chamber (the thorax is the chamber in the case of the heart); and both utilize increasing and decreasing volume as a driving force.[160] At the same time, Erasistratus' heart also differs from a force pump in a number of ways, which makes a *direct* debt hard to establish. The most striking difference is that whereas the pump conducts only water, Erasistratus' heart feeds two independent systems, one with *pneuma* flowing through the left ventricle and into the arteries, and a second with blood flowing through the right ventricle and into the veins.[161] The ventricles expand and contract in alternation, drawing in and expelling their respective substances without mixing the two. The veins and arteries thus represent two separate vascular systems, connected only at their endpoints—structures that we would call the capillary beds. By the time they reach this junction, the respective substances in each vessel (blood and air) have both been used up and therefore do not enter the other system.[162]

Lonie points out the discrepancy between Erasistratus' two-substance heart and Vitruvius' one-substance pump, adding that whereas the heart has separate outflows for its two substances, the pump delivers water from both pistons into a single collection

[160] Von Staden 1996: 94.

[161] For Erasistratus, both air and blood are crucial substances in the body; blood provides nourishment for the body, while *pneuma* "energizes" such activities as digestion, movement, sensation, action, etc.; cf. *Anon. Lond.* 22.49-23.2; Gal. *De usu resp.* 5 K. 4.502; cf. Harris 1973: 225. Similarly, Gal. *De usu resp.* 1 K. 4.471 describes two different types of *pneuma*: vital [ψυχικόν], distributed by the heart, and animal [ζωτικόν], elaborated in the brain. He also claims that Erastratus held that the primary function of breathing was to fill the arteries; cf. Gal. *De diff. puls*. 4.2 K. 8.714; 4.16 K. 8.760.

[162] In other words, Erasistratus adopts Herophilus' anatomical distinction between the veins and arteries while reintroducing Praxagoras' physiological distinction, insisting that veins transport blood, while arteries transport only *pneuma*.

reservoir.[163] Yet, Philo's description—if his account can be trusted—is actually be older than Vitruvius' and depicts a slightly different arrangement, whereby the two pistons work independently. In fact, they are even placed in separate reservoirs. (fig. 7):[164]

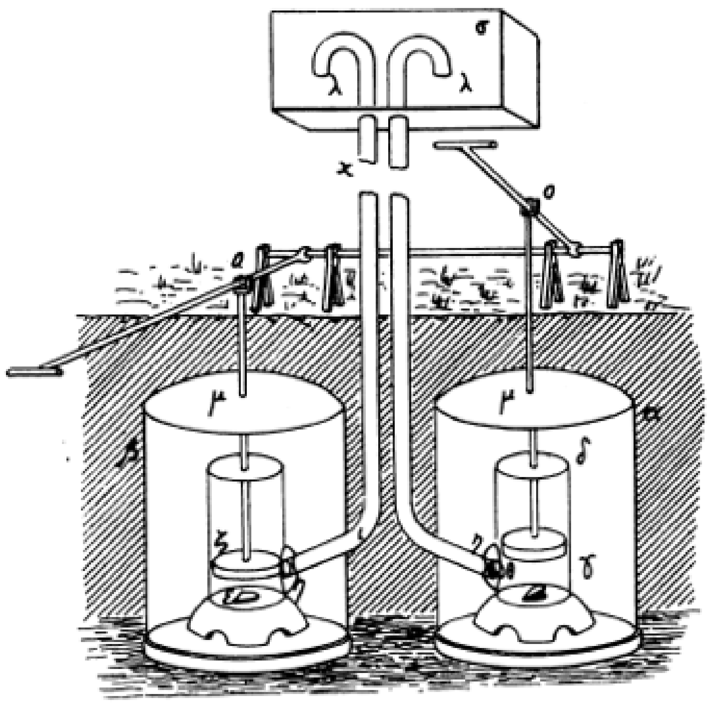

Fig. 7 Philo's Description of Ctesibius' Pump (Carra de Vaux)[165]

> Another apparatus for raising water in an elegant fashion. Get two pots of leather, and let the diameter of each be three hand-spans [*empans*] and the height of two reins [*coudées*]. Let $\alpha\beta$ be the pots. In the middle of each, we will place the body of a solid and vertical pump $\gamma\delta$, on the basis of which we will open an intake valve ε; and let us adapt a piston, which is $o\zeta$. We will make a protrusion on the body of the pump at η, in which the outflow valve θ opens. And so, let us take two pipes and mount them on the protrusion, above the outflow valve; the height of each of these is ten reins; let them be marked $\iota\kappa$. On the top of the piston, at point o, on the

---

163 None of the extant archaeological examples have this reservoir, but are simply connected with a t-joint, Oleson 1984: 309-310.

164 Cf. Oleson 1984: 307-309.

165 Carra de Vaux 1902: 194. Despite their obvious anachronism, I have used Carra de Vaux's figures for Philo's *Pneum*. because without having investigated the manuscript images, I would be basing my diagrams on these fanciful depictions alone. That being said, these images in no way reflect the type of drawings that would have appeared in Philo's text.

> outside, let us place a stem and lever that we can move, and let us attach two hinges to the lever, just like the one we made for the well. At the mouth of the two pots, let us place a cover, μ. It is necessary that, when the piston is drawn upward, the water is breathed in from the pot to the body of the pump, since the intake valve is lifted by the air; and so, the water is drawn up and enters into the body of the pump. When, conversely, the lever is pushed down, the intake valve closes, the outflow valve opens and water climbs into the pipes, into which the mouths run at point λ; it is emptied to that place in the reservoir which has an σ. It is necessary that there be water in both the pots. That is what we wanted to explain. See the diagram (Philo, *Pneum. appendix* 1.2 = 192-194 Carra de Vaux).[166]

In this model, the pumps do not sit in a well or common water source, but rest in two separate leather "pots," which can potentially contain two different liquids. This would allow you to mix the two fluids together in the same outflow reservoir. If that reservoir were removed, however, the force pump's two chambers would operate independently. As such, Erasistratus' two independent systems of vessels agree quite closely with this model of Ctesibius' pump.

Nevertheless, even if the pump's sections sit in two separate basins, they still transfer water alone, whereas Erasistratus' heart moves both blood and air.[167] More than that, there are no pistons in the heart; it functions by dilation and contraction, not push and pull. Most importantly, from Galen's report it seems that Erasistratus does not invoke an analogy with a pump; he compares the heart to the smith's bellows. Despite these discrepancies, directly before describing the dual piston force pump, Philo's text contains

[166] Philo's Greek text is lost, and so we must rely on an Arabic manuscript. I have based my translation on Carra de Vaux's French. Some doubts have been cast on the authenticity of this part of Philo's treatise and whether it contains several interpollations, since it is extant only in an extract; see Prager 1974 for the full transmission history of manuscripts in various languages.

[167] Vitr. *De arch.* 10.8.3 actually says that air and water [*aer cum aqua*] are pushed out. This is a very common interpretation of water pressure in antiquity, ascribing its power to the driving force of air. Conflation of air and water pressure is evident from the very fact that most of the treatises written on hydraulic technology have been titled *Pneumatica*; cf. Plin. *NH* 19.20.60, who calls the force pump the *organum pneumaticum*, and Isidor. *Orig.* 20.6.9, who calls the *sifon* a *vas…quod aquas sufflando fundat*.

a description of another pump that works by dilation and contraction, which is explained by using the bellows as an analogue (fig. 8):

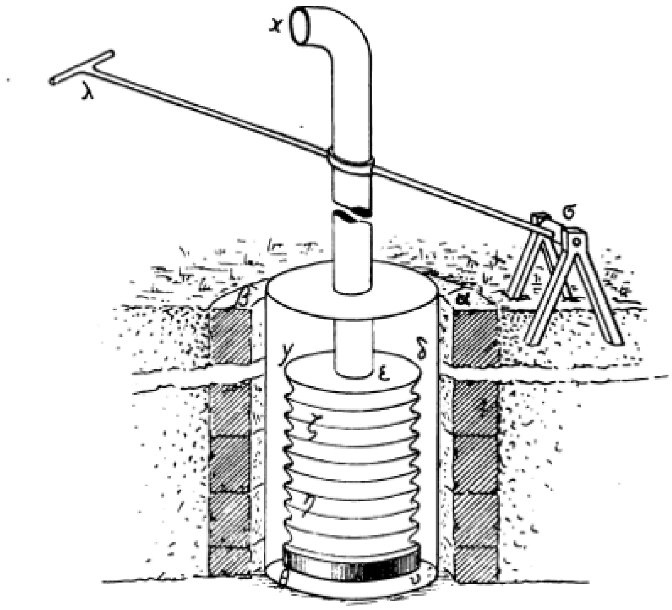

Fig. 8 Philo's Description of the Bellows Pump (Carra de Vaux)[168]

> An apparatus for raising water from the bottom of a well in an elegant manner. Let there be some well; let its size be the same in height and depth and let it be an equal size in circumference. Then, let us cement the well on the bottom of the water, if possible, or cover the soil up with planks or in some other way. Let αβ be the well. Next, make a cover of hard wood fitting exactly into the well, just like a tap; in fitting, it fills up the well without attaching to it and it covers the surface of the water as unbroken and without fault. That cover is γδ. Arrange, on a length that passes a little into the water's depth, rolls made of leather and fitted hermetically around the cover, without any leaks, and resembling the tubes in a conduit. This leather implement is submerged into the water, the length of the cylindrical partitions and to the depth of the well. Inside there are collars that encompass its interior, *of the type that all the instruments that open and close during their movement, just like the goldsmith's bellows open and close,* which are called '*zaaqi*'. The leather device is seen at ζη. Cut a hole into the middle of the cover, at point ε, and in the hole place a pipe of leather or some other substance, long enough to reach out of the well; place a collar of very heavy lead, in a way so that when the collar reaches the bottom of the well, it holds firmly; it is marked θυ. Again, at an appropriate level for the elevation and for the relationship

[168] Carra de Vaux 1902: 192.

> with the depth of the water, arrange a wooden handle so that it attaches to the pipe and which is called a lever; it is marked λ. On the sides of the bottom of the well, on its extremities, this hand is equipped with two very solid columns; these hinges turn easily; let them be marked *σσ* (Philo, *Pneum. appendix* 1.1, 191-193, Carra de Vaux).

Since Philo's text comes *via* an Arabic translation, it is hard to tell what has been interpolated. To be sure, the traditional smith's bellows have become those of the "goldsmith," and it is clear that some author has added their Arabic name, *zaaqi*. This, to my mind, suggests a gloss from the Greek rather than a full-scale interpolation.[169] Indeed, Drachmann holds that because this entry precedes the force pump, it likely describes another of Ctesibius' designs.[170] If this is the case, a less sophisticated and less practical model of a force pump existed that functioned explicitly like the bellows in Erasistratus' heart.

In any case, we should recall that Aristotle used the bellows to describe the heart, but still did not see it as an organ of propulsion, while Herophilus seems to have made the lungs work like bellows, but did not connect them to the vascular system. Now, Erasistratus uses this technological analogy to describe the heart, but attaches it to a heuristic describing the delivery of both *pneuma* and blood. It is hard not to conclude that one of—if not both—the pumps invented in his generation played a crucial role in this re-conceptualization of the bellows as a mechanism that did not only expel air, but could also be attached to a blood-distribution system and act as an engine of propulsion.[171]

---

[169] Moreover, this passage suggests using leather pipes, which are not generally seen in the Greek world (Carra de Vaux 1902: 191 suggests that this practice has its origins in the East). Drachmann 1948: 50-67 notes that the Arabic text of Philo seems to contain many implements that have been reinterpreted to reflect Middle Eastern vessels.

[170] Drachmann 1948: 4-6.

[171] Oleson 1984: 317-318 suggests that the early models were only used for scientific demonstrations until Hero's version, with its pivoting handle, began to be used for firefighting in the Roman period. Later

While direct equivalency between tools and organs can provide dramatic instances when technological heuristics influence the interpretation of the body, pneumatic devices impacted Erasistratus' physiology more than by creating simple one to one comparisons. As described above, he proposes a completely segregated system, in which the arteries contain only *pneuma*, while the veins contain only blood.[172] And, like Plato and Aristotle before him, Erasistratus believes that the body entirely consumes the blood distributed through the veins. Unlike these previous thinkers, however, he insists that any lost blood or *pneuma* must be replaced by an equivalent amount of new material entering the vessels according to the principle ἡ πρὸς τὸ κενούμενον ἀκολουθία. If some air leaves an artery, some new air must replace it simultaneously; if some blood flows out of the veins, the same amount of blood must enter into them. Previous thinkers had applied this idea to respiration, but Erasistratus is the first to apply it to blood distribution. In other words, he fully pressurizes the body.

Along with providing a new mechanism of distributing blood and *pneuma* throughout the body, his pneumatic physiology also created a new framework to understand the etiology of disease. For instance, whereas previous theorists considered the dual function of the veins to be the *normal* state of the body, arguing that the excess of either *pneuma* or blood would cause blockage and disorder, Erasistratus now proposes the opposite, insisting that when two substances *share* a vessel, illness results. He thus inverts a basic physiological assumption held by almost every medical theorist up until his time. This pathologizing of mixture relies upon a pressurized physiology, to be sure,

---

archaeological evidence attests to other uses, including as bilge pumps, well pumps, mining apparatuses, ceiling washers and reservoir pumps for water-jets.

[172] Gal. *De sang. in art.* 8 K 2.624. In this way he seems to be adopting a distinction established by Praxagoras; cf. n. 89, 141.

but more than reflecting a general principle, the way he describes these ailments reflects the particular tasks for which pneumatic devices were being invented at the time. To begin, he does not claim, as his predecessors might have, that blood infiltrating the arteries blocks the pipe outright; rather, he simply states that it "arouses inflammation" [*inflammatio excitat*] and causes fever.[173] In fact, Galen reports that for Erasistratus inflammation cannot occur *without* blood getting into the arteries,[174] and the pseudo-Galenic *Introduction* even claims that Erasistratus ascribes *all* disease to the infiltration of blood into the *pneuma*-filled veins (although this is clearly an overstatement).[175] The shift from pathologies of 'blockage' to those of 'infiltration' suggests that he is conceptualizing the operations of the body as parallel to those of the fine-tuned pneumatic *automata* around him. We need only think of the multiple implements described in Hero's text that function because of the perfect balance of water, wine and air, separated in different chambers. One example can suffice to illustrate this, a dual vessel system, operating by means of vacuum pressure, that maintains separate compartments for water and air (fig. 9):

[173] Celsus, *Med.* 1, *proem.* 15-16; Cf. 1, *proem*. 60; 3.10.3.

[174] Gal. *De usu part.* 6.17 K 3.493; cf. [Gal.] *De hist. phil.* 39 K. 19.342-343; *De loc. aff.* 5.3 K. 8.311; cf. Harris 1973: 204-205.

[175] [Galen] *Intr.* 13, K. 14.728. Erasistratus contends that the arteries and veins are actually connected at their ends (what we would see as the capillary venules and arterioles) by *synastomoses*, small connections through which infiltration can occur. Gal. *De usu part.* 6.17 K. 3.492-494 complains that these would serve no physiological function other than to cause disease; cf. Harris 1973: 209.

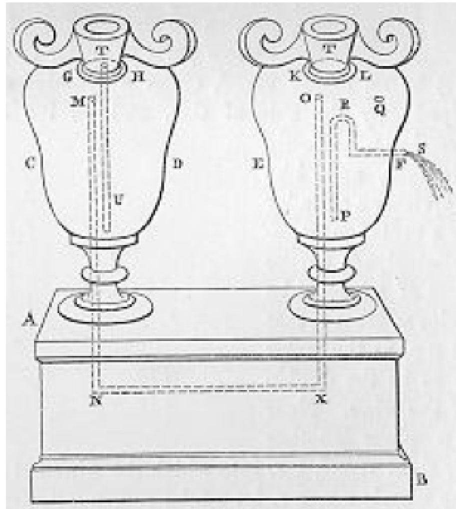

Fig. 9 Hero, *Pneum.* 23 (Woodcroft)[176]

δύο ἀγγείων ὄντων ἐπί τινος βάσεως καὶ τοῦ μὲν ἑνὸς πλήρους ὄντος οἴνου, τοῦ δὲ ἑτέρου ὑπάρχοντος κενοῦ, ὅσον ἐὰν εἰς τὸ κενὸν ἀγγεῖον ὕδωρ ἐγχέωμεν, τοσοῦτος ὁ οἶνος ἐκ τοῦ ἑτέρου ῥυήσεται· κατασκευάζεται δὲ οὕτως. ἔστω ἐπί τινος βάσεως τῆς ΑΒ δύο ἀγγεῖα τὰ ΓΔ, ΕΖ διαπεφραγμένα τὰ στόμια τοῖς ΗΘ, ΚΛ διαφράγμασι. σωλὴν δὲ ὁ ΜΝΞΟ διὰ τῆς βάσεως διώσθω καὶ ἀνακεκάμφθω εἰς τὰ ἀγγεῖα ἀπέχων ἀπὸ τῶν διαφραγμάτων βραχὺ κατὰ τὰ Μ, Ο. καὶ ἐν μὲν τῷ ΕΖ καμπύλος σίφων ἔστω ὁ ΠΡΣ τὴν κυρτότητα ἔχων πρὸς τῷ στόματι τοῦ ἀγγείου· τὸ δὲ ἕτερον σκέλος αὐτοῦ ἐκτὸς φερέτω εἰς κρουνὸν διεσκευασμένον. διὰ δὲ τοῦ ΗΘ διαφράγματος καθείσθω χώνη ἡ ΤΥ, ἧς ὁ καυλὸς συνεστεγνώσθω τῷ διαφράγματι καὶ ἀπεχέτω ἀπὸ τοῦ πυθμένος βραχύ. ἐγκεχύσθω δὲ διά τινος τρυπήματος τοῦ Φ εἰς τὸ ΕΖ ἀγγεῖον οἶνος, ὃ μετὰ τὴν ἔγχυσιν πάλιν ἀπεστεγνώσθω. ἐὰν οὖν ἐγχέωμεν διὰ τῆς χώνης ὕδωρ εἰς τὸ ΓΔ ἀγγεῖον, συμβήσεται τὸν ἐν αὐτῷ ἀέρα ἐκθλιβόμενον χωρεῖν εἰς τὸ ΖΕ ἀγγεῖον διὰ τοῦ ΜΝΞΟ σωλῆνος· ὁ δὲ μεταχωρῶν ἐκθλίψει τὸν ἐν τῷ ΕΖ ἀγγείῳ οἶνον· καὶ τοῦτο ἔσται, ὁσάκις ἐὰν ὕδωρ ἐγχέωμεν. καὶ δῆλον ὅτι ἐκθλιβόμενος ὁ ἀὴρ ἴσον ὄγκον ἔχει τῷ ἐγχυνομένῳ ὕδατι καὶ τοσοῦτον οἶνον ἐκθλίψει. καὶ ἐὰν μηδὲ σίφων ᾖ καμπύλος, ἀλλὰ μόνον κρουνὸς πρὸς τῷ Σ, δύναται τὸ αὐτὸ γενέσθαι, ἐὰν μὴ τοῦ ὕδατος ἡ βία κατακρατήσῃ τοῦ κρουνοῦ.

If there are two vessels on a single base, and one of them is full of wine, while the other is empty, if we pour any quantity of water into the empty vessel, the same quantity of wine will flow from the other vessel. It is made in this way: let there be two vessels on a single base AB with their spouts stopped up by the stoppers ΗΘ and ΚΛ. And let the tube ΜΝΞΟ pass through the base and bend up into the vessel, remaining a short

[176] Woodcroft 1851. I use these diagrams in lieu of my own; cf. n. 165 above.

> distance from the stoppers at M and O. And in EZ let there be a bent siphon ΠΡΣ, having its curve at the spout of the vessel; and let another leg carry outside into the prepared pipe. And let a funnel ΤΥ be situated through the stopper ΗΘ, and let its stem be sealed in the stopper and stop just above the bottom of the vessel. And let wine be poured through a hole at Φ into the vessel ΖΕ, and after pouring it in, seal the vessel again. And so if we pour water into the vessel ΓΔ through the funnel, the air inside will force out and enter into the vessel ΖΕ *via* the tube ΜΝΞΟ. And it will move and force out the wine in the vessel ΕΖ. And this will happen as many times as we pour water in. And it is clear that the air being forced out has an equal mass to the water being poured in and it will force out the same amount of wine. And if there is no curved siphon, but only a pipe at Σ, it will be able to do the same thing, unless the force of the water overpowers the pipe (Hero, *Pneum*. 23).

The above device describes the balanced interactions between fluids and water, and requires that wine be sealed in the vessel ΖΕ. Should that seal be broken and allow unwanted air into this compartment, the vacuum pressure by which the mechanism functions would be lost. In other words, the infiltration of a substance into the wrong vessel causes malfunction.

Many other pneumatic devices described by Hero show the same types of behaviour. In fact, there seems to be a particular fascination with designing mechanisms that distribute two or more separate substances though the interconnected, but segregated actions of water and air. Hero describes mechanisms that pour out liquids of different temperatures (*Pneum.* 7); vessels that distribute wine and water either separately or mixed in different proportions (*Pneum.* 8, 24, 59, 65); two vessels, one of which distributes wine, the other water (*Pneum.* 13); drinking horns that distribute both wine and water (*Pneum.* 18; cf. 52, 64); a vessel that can channel different liquids through a single exit pipe in alternation (*Pneum.* 22); a pipe that distributes wine in proportion to the amount of water removed (*Pneum.* 25); a vessel that distributes wine in proportion to the amount of water added (*Pneum.* 26); a vessel that distributes different kinds of wines according to the weight placed in a cup (*Pneum.* 32); a vessel that stops distributing wine whenever water is poured in (*Pneum.* 39); and a vessel in which air and water alternatively ascend and descend (*Pneum.* 53). In all these cases, the infiltration of water into a vessel designed for air, or wine into a vessel designed to carry water would cause the mechanism to malfunction.[177]

In sum, while Erasistratus relies on ἡ πρὸς τὸ κενούμενον ἀκολουθία to understand the body, when applying his principle to understand the mechanism of disease within the body, he interprets its significance through the pneumatic technologies being developed around him. After all, Plato too denied the possibility of the void, but did not ascribe all diseases to the infiltration of *pneuma* into the wrong vessels. To be sure, without an explicit reference to new pneumatic technologies and pipes, we cannot be certain that Erasistratus implicitly relies on these devices in particular as a material

[177] Some of Hero's devices are inventions that post-date Erasistratus. Nevertheless, it is not hard to see Erasistratus' pathological framework as reflecting similar technologies developed in Alexandria. Yet, Erasistratus' account presents several physiological difficulties that should also be addressed briefly. First, he may additionally have subscribed to some aspects of the cutaneous breathing first suggested by Empedocles, since *Anon. Lond.* 23.89 reports that he held the air-filled arteries to run "into the pores throughout the whole body and then though the pores in the flesh to the outside" [εἰς τὰ καθ᾽ ὅλον τὸ σῶμα ἀραιώματα, εἶτα διεκθεῖ διὰ τῶν ἐν τῇ σαρκὶ φυσικῶν ἀραιωμάτων εἰς τὸ ἐκτός]. This brings up a further question of why the air does not push through the pores. Second, if the entire body were a pressurized system, any *pneuma* that the heart expels into the arteries would have to be immediately replaced by an equal amount supplied by the lungs. As Galen points out, however, if this were true, whenever we stopped breathing, there would be no *pneuma* to fill that space, and the heart would be unable to expand. Put simply, if the lungs and the heart were a connected pneumatic system, when we held our breath, our heart would stop. Indeed, Erasistratus even seems to accept this consequence (cf. Gal. *De usu resp.* 2.3 K. 4.473-475), and his followers argue that the heart in fact does not beat in this situation, but that it merely "oscillates" [κραδαίνεσθαι] (Gal. *De usu resp.* 2.5 K. 4.476). This extreme (and seemingly unsupported) physiological consequence mimics some of the other physiological assertions of the period that still rely on the *clepsydra*. For instance, [Arist.] *De sudore* 25-26 and *Pr.* 2.1.866b9-14 both use the *clepsydra* as an analogue to argue that we do not sweat when we hold our breath on the grounds that the body cannot expel once substance without taking in an equal amount of another; cf. n. 66 above) There is also a third problem: Gal. *An in art.* 2.3 points out that if the arteries were filled with *pneuma*, they should not spurt blood when pierced—as they appear to—but air. Erasistratus' response is that the air immediately exits the punctured artery, creating a vacuum, which draws in blood instantaneously. Galen suggests that if Erasistratus is correct, even the smallest pinprick of an artery should void the entire system of its *pneuma* and cause immediate death; cf. Gal. *De usu part.* 6.17 K. 3.492; cf. *An in art.* 708-709. Galen provides extensive (and exhaustive) criticism of Erasistratus proposal that the arteries contain only air in two separate works: *An in art.* and *De venes*; cf. *Anon. Lond.* 26.31-28.45 for pre-Galenic criticisms.

heuristic, but the fact remains that he applies his abstract principle in a way what takes for granted that his blood vessels function much like the vacuum-pressure driven *automata* around him. Even though it is difficult to assign a direct causal link between the rise of hydraulic technology and the dramatic pressurization of the body, it seems highly probable that the latter followed from the former. With the force pump, Erasistratus now had a machine that functioned like the bellows, but delivered water.

2.2 Asclepiades of Bithynia and Cultural Heuristics

One might presume that the invention of pressurized water-delivery devices forever changed conceptualizations of the vascular system and that after the heart was compared to a force pump, thinkers would never produce another model of the vascular system that is non-pressurized (at least to some degree). Yet, not only does Erasistratus' model present considerable physiological problems, but the history of science is also not simply a history of discoveries and advancements. Instead, theorists draw on their contemporary technological environments regardless of where they might fit in the trajectory of human material endeavour. In this section, I would like to examine how even something as basic as a watercourse can have a profound impact on scientific theories—especially if those watercourses belong to both the technological and cultural fabric of a society, as the aqueducts did in Rome. Just as the Hellenistic era extended technologies already nascent in the classical world, Roman water-delivery systems extended the technologies of Alexandria, but implemented them on a far grander scale. No new natural laws were discovered, so to speak, but as I will show, these water technologies affected medical theories nevertheless—not by providing completely new cognitive tools, as it were, but by presenting a widely understood explanatory framework. I call this set of common assumptions shared by theory-makers and a wider target-audience a 'cultural heuristic.' Up until now, I have attempted to pinpoint moments where authors adopted particular technologies to model phenomena. In this section, I examine something more diffuse, albeit just as crucial to scientific explanations: how technologies produce a basic heuristic that can be employed without even referencing the technology directly. In fact, the very ubiquity of these mechanisms may be so widespread that no reference is even necessary.

Even from the early Republican era, water technology and infrastructure formed a large part of Roman cultural identity, a material manifestation of civic progress and pride. Frontinus (c. 35-103 CE) reports that Appius Claudis Crassus led the Appian aqueduct into Rome in 312 BCE, while Manius Curius Dentatus constructed the (Old) Anio aqueduct in 273 BCE. Servius Sulpicius Galba and Lucius Aurelius Cotta repaired those and added the Marcia aqueduct around 146 BCE, while around 127 BCE the Tepula was constructed.[178] Even the practice of naming these aqueducts after those who had them constructed shows the degree to which civic infrastructure was valourized.[179] Perhaps as a result, by the end of the second century BCE, Rome already possessed an impressive and imposing water-delivery system. By the imperial period, aqueducts and baths were major cultural exports, representing the implementation of Romanness itself, as material emblems of Roman order and power were constructed from stone in mortar in the

[178] Front. *Aq.* 1.4-8.

[179] We might also think of such later examples as Statius' *Silvae* 4.3, which was written to commemorate a road, the *Via Domitiana*.

provinces.[180] As Frontinus says (however self-serving it may have been for him to say so as Manager of the Aqueducts at Rome): "Compare our numerous, necessary structures carrying so many different waters with the obviously idle pyramids or with the other useless—but famous—works of the Greeks" [*Tot aquarum tam multis necessariis molibus pyramidas videlicet otiosas compares aut cetera inertia sed fama celebrata opera Graecorum*].[181] To be sure, the huge arcades regulating the flow of water through systems controlled by *calixes*, governed by laws and overseen by bureaucrats would have provided conspicuous material symbols of empire and power.[182]

Masonry conduits formed the largest portion of these aqueducts,[183] which drew their water largely from springs (although the Tepula drew from a lake, and rivers were also a possible source).[184] These surface conduits were most often covered, but only just below ground level. Even so, they were generally large enough for a human to enter so as to conduct maintenance. They were not designed to run full and water flowed only about a third of the way up the wall. As Hodge states: "it helps to consider the aqueduct almost

---

[180] As Wilson 2008: 296 states: "by the early Principate, aqueducts and public baths had become linked features of Roman urbanism."

[181] Front. *Aq.* 1.16; cf. Dion. Hal. *Ant. Rom.* 3.67.5.

[182] Due to the relative paucity of relevant archaeological evidence within the city walls of Rome, information regarding its domestic supply system is interpolated from evidence found at Pompeii. For a list of the aqueducts at Rome and their construction dates, see Wilson 2008; cf. Evans 1994, who provides an in-depth account of all the aqueducts, their construction dates, route, etc.

[183] Although Vitr. *De arch* 8.6.1 cites only three types of channels (masonry conduits, lead pipes and terra cotta pipes), water systems incorporated other materials as well, including stone-cut channels, earthen trenches, clay-lined gullies and wooden pipes; cf. Hodge 2002: 106. The surface channel, however, made up some 80-90% of the total length of Roman aqueducts; cf. Hodge 2002: 93.

[184] Surface water from lakes and rivers was used far less often, although both the Anio Vetus and Anio Novus drew from the Anio river. Front. *Aq.* 1.4 asserts that Rome drew its water from the Tiber for its first four centuries, although springs and wells supplemented this. Springs generally supplied better quality water.

as an artificial river rather than as a water main."[185] Although aqueducts running into Rome did not need to incorporate inverted siphons thanks to the gradient of the surrounding land,[186] many lines elsewhere in the Empire did include them.[187] Once the water reached the city, it was fed into a settling tank [*piscinae*], which filtered out large debris mechanically.[188] These settling tanks were generally connected to a *castellum divisorium*, which diverted water to the three main delivery points:[189] private homes, public fountains and the baths, the last of which was the largest consumer of water. In private homes, water was channeled to the *impluvium* in the atrium, where it was connected to a lead box fitted with taps that supplied domestic fountains, kitchens, etc.[190] In the baths, water ran into boilers and cisterns through a series of pipes, which allowed waters of different temperatures to be mixed to suit each pool. After use in the various rooms, the water would have been used to irrigate the toilet troughs. In general, any water that was not consumed eventually helped the sewage and drainage system.[191] Aside from the few uses in the home that could be turned off with taps, the whole water system of Rome largely flowed without valves on a principle of constant outtake, so while individual pieces of equipment could be disengaged, the water itself generally needed to

---

[185] Hodge 2002: 2.

[186] Hodge 2002: 17.

[187] For information about inverted siphons during the Roman period, see Ortloff 2009. This technique may have been imported from their contact with Pergamon; cf. M. Lewis 2000b: 647; cf. n. 140 above.

[188] Kleijn 2001: 31.

[189] Vitr. *De arch.* 8.6.1 describes a *castellum* that seems largely idealistic given the archaeological evidence. Front. *Aq.* 78.3 states that there were 247 *castella* in his time.

[190] Jansen 2000: 115; cf. Hodge 2002: 115; Humphrey 2006: 47.

[191] For instance, the most famous drain, the *Cloaca Maxima*, probably built by the Etruscans in the sixth century BCE, had other storm drains and sewers connected to it, which it fed into the Tiber; cf. Humphrey 2006: 49; Camardo *et al.* 2011; Pérez *et al.* 2011.

be turned off at the source, lest the incoming stream simply overflow its channel and burst pipes.

One of the other major concerns in designing these channels is determining their gradient: a steep slope causes a swifter current, which causes considerable wear on the aqueduct itself; by contrast, a gentle slope produces a slower current and less wear, but leads to a rapid accrual of calcium carbonate deposits, or 'sinter.' This build-up constricts the flow of water and can completely block pipes.[192] In fact, sinter accumulated with such speed that workmen needed to chip it away before the channels became clogged and overflowed. Frontinus describes large crews of workmen, who were tasked with this type of repair:[193]

> *Haec duplici ex causa nascuntur*: *aut enim limo conscrescente, qui interdum in crustam indurescit, iter aquae coartatur, aut tectoria corrumpuntur, unde fiunt manationes quibus necesse est latera rivorum et substructiones vitiari*.
>
> These [necessary repairs] arise from two reasons: either lime, which sometimes hardens into a crust, thickens, and the path of the water is constrained, or the walls crumple, whence leaks necessarily damage the sides of the stream and the substructures (Front. *Aq.* 2.122).

Despite its massive and extraordinary scale, the whole system was under threat of blockage and disruption. The pipes needed to be cleaned, maintained and replaced, lest

[192] The minimum gradient needed for gravity-fall conduits according to Vitruvius was 1:200 and 1:4800 according to Pliny. Physical evidence shows that the slopes are as little as 1:1200 and as great as 1:95; cf. Humphrey 2006: 44. Hodge 2002: 216 puts the average gradient of flow somewhere between 3.0 and 1.5 m per km fall.

[193] Front. *Aq*. 2.116-121 describes the crews of workmen and the constant upkeep to which they attended. He mentions two groups, those left by Agrippa to Augustus, numbering 240, and those of Caesar, originally organized by Claudius and numbering 460. Among these groups there were overseers, pavers, plasterers, etc.; cf. *Aq*. 2.96. For a fuller account of *sinter* and its accumulation, see Hodge 2002: 98-105, 228; Wilson 2008: 299-300.

malfunctions cause considerable damage to property and public health.[194] It was a massive, complicated and conspicuous apparatus that required constant attention and upkeep.

The effects that aqueducts had on the history of physiology are hard to pin down, especially since none of the principles involved in aqueducts are new, but simply expand technology already implemented in the classical and Hellenistic worlds. That being said, the increasing conspicuousness of water infrastructure may have influenced the physiological ideas of one thinker in particular, and—perhaps more importantly—increased his popularity: Asclepiades of Bithynia, one of the first Greek physicians to establish a successful practice in Rome.[195] Asclepiades arrived sometime around near the end of the second century BCE and established a considerable patient base.[196] Pliny considered him to be a charlatan, a rhetorician who began to practice medicine only to make a profit and who attracted patients not by the soundness of his ideas, but by proscribing wine, cold water and leisurely activities like being rocked in a swing or taking baths.[197] Celsus displays far less pique towards his predecessor, but still worries that Asclepiades spent too little time with individual patients.[198] It is Galen, however, who acts as his chief detractor, frequently noting the falsity of his ideas and the ridiculousness of his claims. At times Galen addresses these claims with proper

---

[194] Cf. Front. *Aq.* 1.7, which suggests that the Appian and Anio had already fallen into disrepair by the mid-second century BCE. Sewer systems and public toilets suffered this same threat. Despite the fact that water from the baths was diverted through attached public toilets in periodic deluges, much of the excrement would have required manual removal; cf. Camardo *et al.* 2011.

[195] For an account of the arrival of Greek medicine in Rome, see Nutton 2004: 157-170.

[196] For an investigation of Asclepiades' life, see Cocchi 1758, Rawson 1982; Polito 1999.

[197] Plin. *NH* 26.7-9.

[198] Cels. *De med.* 3.4.1.

arguments and lengthy rebuttals, and other moments he simply dismisses Asclepiades' assertions as laughable and unworthy of anyone who has even a rudimentary knowledge of anatomy.[199] Without any extant writings, however, we are left to piece together Asclepiades' ideas from these antagonistic sources, which are written in multiple languages in texts with various transmission issues. Thus, it is difficult to determine a precise picture of Asclepiades' theories. Nevertheless, the broad strokes of his physical and physiological theories are clear: he proposes that the body is full of "passageways" [πόροι] through which "unarticulated corpuscles" [ἄναρμοι ὄγκοι] flow.[200] Disease results when the corpuscles clog the pores and cause blockage.[201]

By "passageways" Asclepiades is not referring to the macroscopic channels of the body, such as veins, arteries and nerves, but an entirely integrated and interconnected system of microscopic, invisible openings that pervade the entire body. Although I hesitate to add an external analogy, we might conceive of the entire body (and its organs) as made of sponge.[202] His ὄγκοι move as though a liquid, flowing through the body's openings according to the principle, "the movement towards what is fine" [πρὸς τὸ λεπτομερὲς φορά]. Asclepiades' explanation of respiration, which likens the lung to a funnel and a medical cupping glass, demonstrates what he means by this principle,:

> Ἀσκληπιάδης τὸν μὲν πνεύμονα χώνης δίκην συνίστησιν, αἰτίαν δὲ τῆς ἀναπνοῆς τὴν ἐν τῷ θώρακι λεπτομέρειαν ὑποτίθεται, πρὸς ἣν τὸν ἔξωθεν ἀέρα ῥεῖν τε καὶ φέρεσθαι παχυμερῆ ὄντα, πάλιν δ' ἀπωθεῖσθαι μηκέτι τοῦ θώρακος οἵου τ' ὄντος μήτ' ἐπεισδέχεσθαι μήθ' ὑποστέγειν· ὑπολειπομένου δέ τινος ἐν τῷ θώρακι λεπτομεροῦς

[199] For the latter, see Gal. *De usu resp.* 2.11.

[200] The ἄναρμοι ὄγκοι are variously referred to as ὄγκοι, στοιχεῖα, *corpuscula* and *moles solidae*.

[201] Blockage can be called ἔμφραξις, ἔνστασις, *statio, obstrusio* or *coacervatio*; cf. Vallance 1990: 7.

[202] There is some precedent in this comparison, since Gal. *Nat. fac.* 2.32 compares Asclepiades' model of the bladder to a sponge.

> ἀεὶ βραχέος (οὐ γὰρ ἅπαν ἐκκρίνεται), πρὸς τοῦτο πάλιν τὸ εἴσω ὑπομένον <τὴν> βαρύτητα τοῦ ἐκτὸς ἀντεπεισφέρεσθαι. ταῦτα δὴ ταῖς σικύαις παρεικάζει· τὴν δὲ κατὰ προαίρεσιν ἀναπνοὴν γίνεσθαί φησι συναγομένων τῶν ἐν τῷ πνεύμονι λεπτοτάτων πόρων καὶ τῶν βραγχίων στενουμένων· τῇ γὰρ ἡμετέρᾳ ταῦθ’ ὑπακούει προαιρέσει.
>
> Asclepiades understands the lung to be like a funnel, but he posits the cause of respiration to be the low density in the thorax, towards which the outside air flows and moves because it is of higher density. And it is driven back out when the thorax is no longer able to receive or contain any more; but since some small quantity of low density always remains in the thorax (for not everything is expelled), towards this the remaining bit travels back up out towards the outside heaviness again. Indeed these things are similar to what happens in cupping glasses. And he says that voluntary breathing happens when the thinnest passageways in the lung are gathered together and the throat contracts; for these things comply with our will (Aët. 4.22.2).

This explanation adopts none of the insights gained through comparing the lungs to the bellows, but instead reverts to a more general concept of attraction guaranteed by a medical cupping glass. How the expansion and contraction of the lungs feature in this account remains slightly underdetermined, replaced by the gathering of thin passages in the lungs, a contraction in the throat and “the movement towards what is fine” [πρὸς τὸ λεπτομερὲς φορά]. There seems to be some basic family resemblance between this type of movement and Erasistratus’ pneumatic ideas, but Asclepiades’ concept differs in a key way: it is about relative density, not vacuum pressure. Moreover, it makes no claims about the possibility of large-scale void, with which it could be potentially congruent. Even within this broad picture, many questions remain unanswered, not least of which are: what are the ὄγκοι and what are πόροι?

In order to address these issues, scholars have largely sought to determine the precise nexus of philosophical influence on Asclepiades’ theories. For instance, Gottschalk posits that Asclepiades’ more or less adopted the theory of Heraclides of

Pontus, who also proposed "unarticulated masses" [ἄναρμοι ὄγκοι] as the essential constituents of matter.[203] Others, such as Harig, Casadei and Leith have argued that Asclepiades' "masses" and "pores" are equivalent and analogous to Epicurean "atoms" and "void."[204] In fact, Galen—our chief source for Asclepiades—states this idea explicitly:

> εἰ μὲν γὰρ ἐξ ἀτόμου καὶ τοῦ κενοῦ κατὰ τὸν Ἐπικούρου τε καὶ Δημοκρίτου λόγον συνειστήκει τὰ πάντα, ἢ ἔκ τινων ὄγκων καὶ πόρων κατὰ τὸν ἰατρὸν Ἀσκληπιάδην· καὶ γὰρ ἀλλάξας τὰ ὀνόματα μόνον καὶ ἀντὶ μὲν τῶν ἀτόμων τοὺς ὄγκους, ἀντὶ δὲ τοῦ κενοῦ τοὺς πόρους λέγων τὴν αὐτὴν ἐκείνοις τῶν ὄντων οὐσίαν εἶναι βουλόμενος…
>
> …everything is composed from atom and void according to the account of Epicurus and Democritus, or from certain masses and pores, according to the physician Asclepiades (for he exchanged the names alone and said 'masses' instead of 'atoms,' 'pores' instead of 'void,' while wanting the essence of what exists to be the same as those things) (Gal. *Ther. ad Pis*. 11 K. 14.250).[205]

To determine whether Galen is right, however, we should look at what else Asclepiades reportedly said about ὄγκοι and πόροι. Ultimately, however, I am not interested in their strict philosophical lineage, but in how Asclepiades employs these concepts in action. Nevertheless, it is important first to be as precise as possible in regards to their natures.

[203] Gottschalk 1980: 37-57; cf. Lonie 1964 and 1965. The major problem with this argument is that we know even less about Heraclides than Asclepiades.

[204] Harig 1983: 44-45; Casadei 1997: 77-78, 89; Leith 2009, 2012; cf. Wellmann 1908: 695, who holds that Asclepiades' theories can be traced *via* Erasistratus to Aegimius of Elis; for these references and arguments, see Leith 2012: 165, n. 1. Vallance 1990: 123-147 has also tried to stress that Asclepiades' πρὸς τὸ λεπτομερὲς φορά was both derived from and responded to Erasistratus' ἡ πρὸς τὸ κενούμενον ἀκολουθία. For arguments against this view, see below.

[205] Galen levels his extensive critique of Asclepiades across multiple works, including *Nat. Fac.* and *De usu part.*, but several of Galen's treatises dealing this predecessor are lost, including *On the Opinions of Asclepiades*; cf. Gal. *Lib. prop.* 8 K. 19.55.

For Asclepiades, ἄναρμοι ὄγκοι are invisible, elemental corpuscles that compose all matter. They possess no qualities (which they only manifest in combination),[206] differ only in size and shape (and perhaps magnitude)[207] and are constantly in motion.[208] On the one hand, because Epicurean atoms share many of these features, Leith concludes that Asclepiades must have indeed adopted a broad atomistic framework for his physics. On the other hand, one key difference distinguishes Asclepiades' ὄγκοι from any type of atoms: his corpuscles are frangible and divisible.[209] When ὄγκοι meet each other, they either combine to form larger structures or break into smaller pieces.[210] As Caelius Aurelianus, a second century CE Methodist physician sympathetic to Asclepiades, writes: "[These corpuscles] by their own rushing are struck by mutual blows and broken up into infinite fragments of parts" *quae suo incursu offensa mutuis ictibus in infinita partium fragmenta solvantur*].[211] Some commentators have argued that these smaller fragments constitute a more fundamental type of matter. Despite these arguments, however, as Leith has shown, these *fragmenta* are simply smaller ὄγκοι,[212] different in quantity/magnitude, but not in quality/kind. As such, Asclepiades' physical theory resembles Epicurean atomism, but differs insofar as his corpuscles are not actually in-divisible [ἄ-τομα].

---

206 Cf. Gal. *Elem. sec. Hipp.* 5.1.2 K. 1.416-417.

207 Cf. Cael. Aur. *Acut.* 1.105-106.

208 Cf. Cael. Aur. *Acut.* 1.105: *aeternum moventia*; Sext. Emp. *Ad math.* 3.5: δι᾽αἰῶνος ἀνηρεμήτων.

209 Cf. Gal. *Const. art. med.* K. 1.249, which refers to the "unarticulated [mass] being frangible" [τὸ ἄναρμον θραυστὸν ὄν]; cf. [Gal.] *Intr*. K. 14.698; Sext. Emp. *PH* 3.33: θραυστά.

210 Vallance 1990: 42-43 argues that the means the ὄγκοι are infinitely divisible.

211 Cael. Aur. *Acut.* 1.105.

212 Cf. Pigeaud 1980: 194-198; Casadei 1997: 91-101. Leith 2009: 289-290 argues that Asclepiades only ever mentions the ὄγκοι, which, when they meet each other, either break into smaller piece, or combine into larger objects.

As for Asclepiades' πόροι—which sources also refer to as ἀραιώματα,[213] κενώματα,[214] *foramina* and *viae*[215]—we should ask whether they represent a version of Epicurean void, as Galen suggests.[216] Vallance has argued against this, positing that Galen was merely ascribing a doctrine to Asclepiades so as to launch polemic attacks, all while keeping his other intellectual antagonists, the Methodists, in mind.[217] As Leith points out, however, there is no real evidence to reject Galen's claims or to see another target behind his comments about Asclepiades. Moreover, several of Aslecpiades' arguments about the pores seem to parallel those of the Atomists.[218] As such, Leith suggests that the πόροι should not be thought of as channels at all and should only be understood as "gaps" or "interstices" in matter.[219] In this way, he contends that Asclepiades' πόροι are "exactly analogous" to Epicurean void.[220] For all the strength of Leith's arguments, however, I would like to suggest that even if the πόροι have the strict

---

213 Gal. *Meth. Med.* 2.4 K. 10.101; 13.2 K.10.876; cf. *Comp. Med. Gen*. 6.16 K. 13.936, although Leith 2012: 181, n. 44 argues that this latter passage refers to the first century CE pharmacologist Asclepiades Pharmacion.

214 [Gal.] *Int.* K. 14.698.

215 Cf. Vallance 1990: 7; Leith 2012: 181.

216 Cf. Gal. *SMT* 1.14 K. 11.405; *De usu part.* 6.13 K. 3.474; *In Hipp. Epid.* K. 17B.162. Calc. *In Tim.* 214 also relies on a *Placita* tradition that cast Asclepiades as a void theorist; cf. Mansfeld 1990: 3112-17; Switalski 1902: 53; Polito 2007. Similarly, both [Gal.] *Intr*. K. 14.698 and [Hero], *Def*. 138.8 refer to the ὄγκοι and πόροι as having the status of elements, just like atoms and void. For all these passages, I owe Leith 2012: 166-167, 171-173.

217 Vallance 1990: 57. For doubts about his arguments, see von Staden 1992; Asmis 1993.

218 For instance, *Anon. Lond*. 39.10-15 presents Asclepiades' doctrine of growth as supported by the fact that body does not pass through body, which parallels earlier arguments made by the Atomists that the Epicureans pick up in turn; cf. Arist. *Ph.* 213b18-20; Themis. *In Phys.* 124.4-9; Simpl. *In Phys.* 651.2-8; cf. Leith 2012: 173-177. There are textual issues regarding the passage in *Anon. Lond*. that prevent outright acceptance of his argument. In addition, Leith 2009: 300-305 argues that Asclepiades' soul atoms may have been "smooth and fine," just like the Atomists' soul atoms—a fact that further supports his claims; cf. Cal. *In Tim.* 215.229-230 Waszink.

219 Leith 2009: 181-182.

220 Leith 2012: 164.

philosophical meaning of interstices and operate within a physics similar to atoms and void, calling them "passageways" activates certain physiological arguments that calling them "void" [τὸ κενόν] cannot. Perhaps most importantly, claiming that the body is comprised entirely of πόροι allows for a type of scale-conflation, whereby the macro-vessels of the body become a guarantor of the heuristic that governs the micro-vessels that cannot be seen. It is patently obvious that fluids pass through certain bodily passageways, and thus, by presenting a physiology that relies on the transfer of fluid-like corpuscles, these large-scale corporeal structures become visible evidence of the invisible entities that Asclepiades proposes.

In any case, to understand what arguments πόροι activate for Asclepiades, we should examine how they operate in the body,[221] focusing especially on the etiology of disease. Whereas Erasistratus privileged "infiltration" in his theory of fever and inflammation, Asclepiades reverts back to a blockage model, ascribing all disease to obstruction [ἔμφραξις, ἔνστασις, *statio*, *obstrusio*, *coacervatio*].[222] Celsus reports this information:

> *alia*, *si in umidis omne vitium est*, *ut Herophilo visum est; alia*, *si in spiritu*, *ut Hippocrati*; *alia*, *si sanguis in eas venas*, *quae spiritui accommodatae sunt*, *transfunditur et inflammationem*, *quam Graeci* φλεγμόνην *vocant*, *excitat*, *eaque inflammatio talem motum efficit*, *qualis in febre est*, *ut Erasistrato placuit*; *alia*, *si manantia corpuscula per invisibilia foramina subsistendo iter claudunt*, *ut Asclepiades contendit.*
>
> [Certain treatments are required], if all ill-health is caused by humours, as in seen in Herophilus; other treatments, if blood infiltrates those veins in

[221] To be sure, Leith 2012: 187 admits that even if Asclepiades' physical theory entailed that there were interstitial gaps in all matter, he was only truly interested in using these theories to explain the disease and pathologies of the body, not to examine the physical or ontological implications. Leith suggests nevertheless that Asclepiades could have dealt with the physical implications of his theory in his work *On Elements*.

[222] Vallance 1990:7.

> which *pneuma* is held and causes inflammation, which the Greeks call φλεγμόνη [*fever*], and this inflammation produces such motion as in found in fever, as seemed correct to Erasistratus; others, *if dripping corpuscles clog the way through these invisible passageways by blockage, as Asclepiades contends* (Cels. *Med.* 1. *proem.* 15-16, emphasis mine).[223]

The pseudo-Galen author of the *Introduction* summarizes the differences between Erasistratus and Asclepiades even more concisely:

> κατὰ δὲ Ἐρασίστρατον καὶ Ἀσκληπιάδην, ὡς ἐπίπαν μίαν αἰτίαν ἐπὶ πάσης νόσου, καθ᾽ ὃν μὲν ἡ παρέμπτωσις εἰς τὰς ἀρτηρίας τοῦ αἵματος· καθ᾽ ὃν δὲ ἡ ἔνστασις τῶν ὄγκων ἐν τοῖς ἀραιώμασιν.
>
> According to Erasistratus and Asclepiades, there is only one cause of all disease: for Erasistratus it is the infiltration of blood into the arteries; for Asclepiades it is the blockage of corpuscles in the pores ([Gal.] *Intro.* 13, K. 14.728).

Caelius Aurelianus confirms this account of Asclepiades' doctrines:

> *fieri etiam vias ex complexione corpusculorum intellectu sensas, magnitudine atque schemate differentes, per quas sucorum ductus solito meatu percurrens si nullo fuerit impedimento retentus, sanitas maneat, impeditus vero statione corpusculorum morbos efficiat.*
>
> Still, from the interweaving of corpuscles there comes to be pores intelligible to reason, different in size and shape, through which a duct of liquids flows by an accustomed path; if it should be obstructed by no impediment, health remains, but obstruction by the blockage of corpuscles causes diseases (Cael. Aur. *Acut.* 1.106).

Many other passages confirm that Asclepiades relies *almost* exclusively (although not entirely) on a pathology of "flow" and "blockage." Among the diseases he ascribes to types of flow, he includes phrenitis,[224] pleuritis,[225] pneumonia,[226] sore throat[227] and

---

[223] Cf. Sext. Emp. *Ad math.* 3.5.

[224] Gal. *De exp. med.* 28 states that for Asclepiades, phrenitis is caused by fever and blockage in the cerebral membrane; cf. Cael. Aur. *Acut.* 1.6.

[225] Cael. Aur. *Acut.* 2.89.

[226] Cael. Aur. *Acut.* 2.142.

cholera.[228] Diseases caused by various types of blockage include heart attacks,[229] headaches[230] and diarrhea.[231] While it may seem counter-intuitive to attribute diarrhea to blockage, Asclepiades reportedly argued that the crowding of the corpuscles in one part, led to their overflow in another. Moreover, either flow or blockage can evidently cause fever,[232] although Galen states that Asclepiades reduced all fevers ultimately to ἐμφράξεις.[233]

Cassius Iatrosophista, a second or third century CE follower of Asclepiades and author of a medical treatise entitled *Physical Problems*, presents another instance where Asclepiades' bodily flux theory is employed to discuss broader human physiology, asking: why it is that when someone stubs their foot, bruising only occurs in a given area, but areas even further away can also be affected, such as when glands swell? He provides a potential answer:

> ὁ οὖν Ἀσκληπιάδης ἐν τῷ περὶ ἑλκῶν φησιν ὅτι πρὸς τὰ πληττόμενα κατ' ἀρχὰς ἡ ὕλη φέρεται, καὶ φερομένης αὐτῆς, ὅσον μὲν δύναται ὑποδέξασθαι τὰ πεπονθότα μέρη, αὕτη χωρεῖ εἰς αὐτά· πληρωθέντων δὲ τούτων, καὶ μὴ δυναμένων ἐπιδέξασθαι ἕτερον πλῆθος, ἡ φερομένη ὕλη ἐκρέουσα καὶ μὴ ὑποδεχθεῖσα ὑπὸ τῶν μερῶν, ἐφ' ἃ ἠνέχθη, εἶτα φερομένη, ἐὰν ἐπιτύχῃ κοίλων τόπων,

---

227 Cael. Aur. *Acut.* 3.5.

228 Cael. Aur. *Acut.* 3.188.

229 Cael. Aur. *Acut.* 2.163.

230 Cass. Iatr. *Pr.* 77.

231 Cael. Aur. *Acut.* 3.220.

232 Cael. Aur. *Acut*. 1.8.

233 Gal. *De trem. rig. et palp.* K. 7.615; cf. *De dieb. decr.* K. 9.798. Along with a physiological theory, Asclepiades' model of flow might have epistemological ramifications as well. Sext. Emp. *Ad math.* 8.6-7 links it to the flux-theory of reality first posited by Heraclitus, stating that Asclepiades claimed that the same river cannot be pointed out twice "because of the speed of the stream" [δύο δείξεις διὰ τὴν ὀξύτητα τῆς ῥοῆς]. Similarly, Gal. *De secti* K. 1.75-76 connects this back to the idea that the corpuscles move perpetually, and thus the body stays in constant flow.

> μένει εἰς αὐτούς, ὥσπερ καὶ ἐπὶ τῶν ὑδάτων ἔχει. ταῦτα γὰρ ἕως μὲν ἐπ' ἰσοπέδῳ φέρεται, ὁμαλῇ τῇ κινήσει χρῆται· τυχόντα δὲ κοίλων τόπων, μένει εἰς αὐτούς. ταὐτὸν οὖν συμβαίνει καὶ ἐπὶ τῆς φερομένης ὕλης ἐπὶ τὰ πληγέντα. ὅσην γὰρ ὑποδέξασθαι δύναται, αὕτη χωρεῖ εἰς αὐτά· ἡ δὲ λοιπὴ εἰς κοῖλα, καὶ μᾶλλον εἰς ἀραιοπόρους ἐμπίπτει τοὺς βουβῶνας, καὶ διογκοῖ τούτους. ἔστι μὲν οὖν καὶ αὕτη πιθανὴ ἡ ἀπολογία· αἰτιάσαιτο δὲ ἄν τις καὶ τὸ πάνυ εὐπαθὲς τοῦ νευρώδους· τοῦτο γὰρ δι' ὑπερβάλλουσαν εὐπάθειαν, θᾶττον τῶν ἄλλων μερῶν τοῦ σώματος, συμπαθεῖ τοῖς πεπονθόσι μέρεσι. διὰ τοῦτο γοῦν καὶ κατὰ τοὺς ἀδένας χοιράδες συνίστανται περὶ τράχηλον, ἑλκῶν ὄντων περὶ τὴν κεφαλήν. καὶ βουβῶνες ἐν μασχάλῃ, ἑλκῶν περὶ χεῖρα ὄντων.
>
> In his *On Wounds*, Asclepiades says that material is first carried to the parts that have been struck. The material is carried there and approaches the affected parts in proportion to their ability to accept it. When they are full, and can take in no more, the matter carried there flows out, and since it has not been accepted by the parts to which it was borne, it is then carried on. If it reaches hollow places it stays in them, as happens in the case of water, which, as long as it is born along on a level surface, uses an even motion, but on coming across hollow places it remains in them. The same thing happens to the material that is borne towards the parts that have been struck. As much material as can be accommodated moves into them, but the rest goes into hollow spaces, and especially into the glands with their fine pores, making them swell. This is a convincing argument (Cass. Iatr. *Pr.* 40).[234]

The passage does not declare what type of channel this water is flowing in before it spills over into the "hollow spaces," but it is clear that regardless of the philosophical underpinnings that Leith has drawn out, Asclepiades himself exploited, or at least conflated, the notions of a 'void' and of a 'passageway' in the human body. If the body was simply a giant sponge of interstices in which fluids moved according to their relative densities, bruising and soreness should affect surrounding areas in direct proportion to proximity. His use of πόροι allows him to involve watercourses as part of his physiology.

---

[234] Cf. Cass. Iatro. *Pr.* 1, which discusses why a round wound does not heal as fast with recourse to the observation that a river is stronger at its centre, and thus the flow of material in the centre of the wound must keep that spot from healing quickly; cf. *Pr.* 346, which asks why nearby parts of the body do not suffer when something is wounded right beside them, and uses an analogy with flowing water to do so.

In fact, Asclepiades' physiology reduces the entire complex of the human system into a basic system of flow and blockage, and this in turn relies on aqueducts in two key ways.

To begin, the fact that Asclepiades describes the water in the above quotation as flowing 'level' certainly does not reflect either a pressurized pipe or an interlocking network of interstices. Given the amount of technical sophistication that was required to level aqueducts[235] and the ostentatious straight lines that aqueducts produce across the horizon, we might be more inclined to conclude that Asclepiades is imagining some sort of man-made, open air watercourse. Other passages seem to indicate that Asclepiades incorporates other particular features of aqueducts into his physiology. For instance, Caelius Aurelianus preserves a passage that mentions again how blockages occur:

> *Fit autem eorum statio aut magnitudinis aut schematis aut multitudinis aut celerrimi motus causa, aut viarum flexu conclusione atque squamularum *exsputo* varias inquit fieri passiones locorum aut viarum differentia.*
>
> …however he says that a blockage of these [corpuscles] is caused by the size, shape, multitude or speed, or he says that different affections arise by the bending of the passageways and by the *blockade of scales in different places and passageways* (Cael. Aur. *Acut.* 1.107, emphasis mine).

Editors have had considerable trouble with this passage, especially with "scales" [*squamula*] and have offered multiple emendations as a result. Drabkin emended the second sentence to read "*conclusione corpusculorum effecto*,"[236] while more recently, Vallance has simply stated that "little scales" [*squamula*] refer to *fragmenta*, and thus indicate corpuscles that have broken off the sides of the passageways.[237] I would like to suggest that no emendation of *squamularum* is necessary and that the term likely refers to

[235] Vitr. *De arch.* 8.5 mentions the *dioptra* and the *chorobates*.

[236] Drabkin 1950; cf. Vallance 1990: 115 for references to other editions.

[237] Vallance 1990: 114-115.

the ‘lime-scale’ that forms on the inside of waterways that I mentioned above. In other words, Vallance is correct in seeing them as fragments from the sides of the micro-passageways, but we should recognize that Asclepiades likening these particles to the sinter that needed to be constantly chipped off to prevent overflows and blockages.

Another feature of Asclepiades’ disease etiology reflects Roman water infrastructure. It occurs when he explains dropsy:

> *Et non omnes statione corpusculorum sed certas, noc est phrenitim, lethargiam, pleuritim et febres vehementes; solubiles vero liquidorum atque spiritus turbatione. Item bulimum magnitudine viarum stomachi atque ventris fieri sensit* [sc. Asclepiades]; *defectionem vero atque corporis fluxam et irregibilem laxitatem viarum inquit raritate fieri*; *item hydropsimum perforatione carnis in parvam formulam viarum quae posit solita corporis nutrimenta inaquare*.
>
> And not all diseases arise from the blockage of corpuscles, but certain ones do, like phrenitis, lethargy, pleurisy and severe fevers; fluid diseases are caused by the disturbance of liquid and *pneuma*. In this way, Asclepiades thinks that bulimia arises because of the size of the pores in the stomach and in the abdomen; he says that fainting and the flux of the body, as well as uncontrollable laxity arise because of the looseness of the pores; in the same way, *dropsy arise by boring a small conduit into the flesh*, which is able to turn the accustomed nutrition of the body into water (Cael. Aur. *Acut.* 1.107-108)

This language of “boring” a small conduit [*formula*][238] into the flesh reflects a difficulty that Frontinus latter describes in *De aquaeductu*, namely that people illicitly bored holes into water pipes in order to draw water for their own personal use without paying taxes for the connection. He describes this *fraus* as a major problem that he intends to solve:[239]

> *Sed et plerique possessorum e quorum agris aqua circumducitur, formas rivorum perforant, unde fit ut ductus publici hominibus privates vel ad hortortum usus itinera suspendant*.

[238] Cf. Front. *Aq*. 1.37 for this use of *formula*.

[239] Volk 2010 examines this type of theft and its poetic use in Manilius.

> But many land owners whose fields the aqueducts flow around *bore into the conduit* of the stream, whence it happens that private citizens stop the public watercourses just to use it for their gardens (Front. *Aq.* 1.75).[240]

It does not take any particular doctrinal commitment to interpret dropsy—the visible accumulation of fluid—as an unsanctioned boring [*perferatio*] into a fluid-carrying vessel. Nevertheless, it shows precisely the type of scale-conflation that can occur between Asclepiades' micro- and macro-passageways in the body, as he moves between the unseen pores within the body and their larger, visible counterparts.

To be sure, Asclepiades was certainly not the first thinker to explain diseases as caused by bodily obstructions, and, as we have seen most demonstrably in *On the Sacred Disease's* explanation of epilepsy, pathological blockage is a common idea for the Hippocratics, as well as for Diocles, Praxagoras, Timotheus of Metapontum and Aegimus of Elis.[241] Anyone who has a body should understand why, since obstructed nasal passageways, blocked ducts, stopped digestive tracks, etc. form many common illnesses.[242] Nevertheless, contemporaneous water technology buttressed his scientific arguments. When pneumatic technology was *de rigeur* in Alexandria, pressurized and finely tuned water technologies seem to have infiltrated Erasistratus' physiology of the body and his etiology of disease. When the massive water infrastructure began to dominate the technological landscape, Asclepiades proposed a physiology based fundamentally—and to a degree never before encountered—on passages, flow and blockage. The ubiquitous presence of the aqueducts and water pipes in Rome, all of

[240] Cf. Front. *Aq.* 2.87; 2.115; 2.128.

[241] See Vallance 1990: 98-99 for references; cf. Lonie 1981.

[242] Vallance 1990: 101 argues that ἔνστασις, however, was first used as a technical term by Asclepiades. On the universality of the corpuscular hypothesis, see *Anon. Lond.* 39.22-32.

which required maintenance teams to be kept clear, lest they overflow, impacted Asclepiades' assumptions about the unseen structures of the body. His daily, material world functioned as his cognitive world. At any rate, his theory demonstrates that the history of scientific principles is neither linear, nor confined to an abstract realm of logical cohesion. Rather, principles are both derived from and embodied within the technologies surrounding each thinker.

There is, of course, a glaring question that remains to be answered. Why was it Asclepiades, a Greek from Asia Minor, who was responsible for a physiology that seems to reflect Rome's technological environment? If the 'cognitive infrastructure' provided by Rome was new, even if by degree, not by kind, why did a Greek produce a physiology reflecting this? Did he come to the city without any such ideas, only to make them up once he saw the ubiquitous aqueducts? Was he deliberating shaping his explanations based on his Roman audience? There are multiple things to be said in response to these questions. First, it is unreasonable to suppose that Asclepiades developed his medical theories only upon reaching Rome, since he was a physician prior to his arrival and perhaps even spent time in Alexandria studying.[243] Polito suggests that Asclepiades developed his scientific and philosophical views in Alexandria, and deviated from these conclusions later in life.[244] If this is true, it could mean that while there is a philosophical lineage for his concept of pores and corpuscles, the translation of these concepts into physiological ideas—those involving blockage and flow in watercourse-like passageways—took place in Rome. I am, however, loath to accept anything so question-begging for my argument. Instead, we should recognize that Pergamon too had developed

[243] For accounts of Asclepiades' dates and other biographical information, see Rawson 1982; Polito 1999.

[244] Polito 1999: 63-65.

considerable water infrastructure during this same period, including extremely high-pressure inverted siphons and large-scale aqueducts. Given that Asclepiades has some connection with that city, as well as with the Hellespont and Athens,[245] we can accept that the channels and pipes of cities in his birth-region could easily have influenced his fundamental assumptions about the body, far before he set foot in Rome itself. On a more basic level, however, the simple idea of flow and blockage does not require something so grandiose as the *Pont du Gard* or the Madradag inverted siphon for its inception. We have seen the idea as far back as medical theories go, and the very experience of having a body can suggest this physiological framework, even if the rising significance of water infrastructure in the Mediterranean matched the rising importance of similar infrastructure in the body.

These difficulties allow us to ask another question instead: why was Asclepiades' particular physiology so *popular* in first century BCE Rome? If his medical theories simply deployed Epicurean ideas to explain human physiology, why were his particular arguments so well received? He was so popular that Pliny felt he had to fabricate an explanation for it, and he was influential enough for Galen to attack almost three hundred years later. Cicero cites his rhetorical skill, which was superior to other physicians,[246] while Pliny claims that Asclepiades was trained as a rhetorician before he turned to pursue a fraudulent career in medicine and that he relied on his power of persuasion to attract patients.[247] The other commonly cited reason for his popularity is that he pampered his patients (in contrast to other Greek physicians, who were seen as knife-

[245] Polito 1999: 63; cf. Rawson 1982: 366-7.

[246] Cic. *De Orat.* 1.62.

[247] Plin. *NH* 26.12.

happy butchers). Yet, Celsus suggests that Asclepiades was not always so gentle after all, but that "when he had exhausted the patient for three days with total abstinence, he prescribed food on the fourth" [*Asclepiades ubi aegrum triduo per omnia fatigarat, quartum diem cibum destinabat*].[248] Although more lenient treatments such as moderate wine and 'rocking' were prescribed thereafter, Asclepiades' remedies do not seem wholly comparable to spa-treatments. His popularity therefore does not seem to be fully explained by the fact that he prescribes solely pleasurable remedies. Moreover, even if his rhetoric won him patients in the short term, it does not explain how he established a medical succession, with disciples across the Roman Empire for several hundred years after his death.[249] We cannot attribute this legacy solely to his personal mellifluousness. Rather, his explanations of πόροι and blockages provided a model of the human body extremely persuasive and comprehensible to a Roman populace of his era, who would have based their physical assumptions on the technologies they saw around them every day. Their city worked on blockages and flows in a way completely transferable to the human body. Asclepiades' arguments—whatever their specific medical or philosophical merit—seem to tap into a shared, cultural heuristic. Imagining that scientific ideas get developed in some philosophical vacuum, wherein the influence of one's predecessors is the only palpable force, would be to miss how medical ideas need not only to be logical, but also accessible and convincing.

[248] Cels. *De med.* 3.4.6.

[249] Papyrological evidence attests to a school of doctors proclaiming themselves to be Asclepiadeans up until at least the third or fourth century CE; cf. *CIL* XII 1804 (*ILS* 7790) Limony ad Rhodanum; Bean & Mitford, DAWW 102 (1970), 65 no. 38 [Samama no. 350], Cibyra Minor, Pamphylia. See also Cael. Aur. *Acut.* 3.113 and Plin. *NH* 29.6, who name other Asclepiadeans. For all these references I owe David Leith.

To be clear, I am not arguing that Asclepiades possessed a philosophically rigourous physical and physiological theory that he translated into a form more palatable to a broader audience. Instead, his heuristic of flow and blockage form the core of his conceptualization of the body. This is how he thinks about human physiology; it is not merely some window dressing for a gullible public. Basic ideas about watercourses guide the way that he deploys his principles. Since Asclepiades left no extant treatises, it is hard to determine the precise degree to which he used specifically Roman aqueducts as his cognitive tools rather than more generic watercourses. Yet, it is perhaps because of the ubiquity of πόϱοι in the daily life Romans that an explicit connection with the aqueducts is unnecessary. Indeed, their physical and mental worlds were in effect already built on them. Asclepiades could simply be adopting a set of shared assumptions felt by the populace so strongly as to need no explanation. By employing his basic heuristic, he provides the Roman public with an adaptable and comprehensible model to conceptualize somatic processes.

2.3 Conclusion

In the last two sections, I have illustrated how changing water technologies affected both the formulation and popularity of physiological ideas about the body. During the Hellenistic period, the rise of complex pneumatic devices provided a closer and more in-depth look at a set of physical behaviours displayed by water and air (and wine), and these observations produced and interacted with new ideas about interstitial void and the physiology of the vascular system. As we have seen, however, the resultant theories cannot easily be divorced from the context of their own discovery, insofar as the application of these ideas within physical explanations remains bound up with the devices that embody them. Abstract principles alone are somewhat inert, applicable in a number of different ways to any given physical situation. When these ideas are materialized within certain technologies, however, the latter can establish heuristics that activate corollary claims and guide the ways in which the relevant principle decodes the physiology of the body.

In the last section, I examined Asclepiades of Bithynia, who, despite his greater philosophical commitments to a corpuscular version of Epicurean atomism, adopts a heuristic based on the every-day experience with aqueducts. In this way, particular behaviours of aqueducts, including *sinter*-blockage and illegal boring, seem part of Asclepiades etiology of disease. In addition, I expanded beyond theory construction to suggest that a technological environment can facilitate theory-reception, insofar as a technological world can create a common cognitive world for both a theorist and his audience—in this case the sick patients whom Asclepiades needs to persuade to pay for care. The material infrastructure of the ancient world then becomes part of a conceptual infrastructure. Even if these instances are not as blatant as the analogy found in Empedocles' explanations of respiration, they still provide examples of how the conceptual strength of technologies operates as a core part of theory-formation.

CHAPTER THREE
THE MATERIAL TECHNOLOGIES OF VISION

3.0 Introduction: A Technological History of Vision

In classical antiquity, tools as simple as lamps, mirrors and wax imprints were used to aid sight, manipulate light and retain and transfer images. I refer to this broad group of implements—and any other tools used for the same or similar tasks—as optical technologies. Quite frequently, authors adopted these optical technologies as comparative models to comprehend and conceptualize one or more features in the process of vision. They used their literal tools as cognitive tools, employing them as heuristics to interpret and explain natural phenomena. As was seen in the previous chapters, ancient theorists often fail to impose clearly defined boundaries between analogical and literal descriptions. This chapter too will demonstrate how in this way particular material aspects of ancient Greek optical implements find their way into physical explanations of vision and the physiology of the eyes. In other words, while many ancient theorists say that the eyes are *like* lamps or mirrors or wax, in the course of their arguments, eyes functionally *become* lamps and mirrors and wax. As a result of this slippage—what I have called 'analogic drift'—individual technologies essentially function as theories and begin to predicate physical features not otherwise observed. In this chapter, I will use this concept to examine optical explanations in the fifth and fourth centuries BCE, focusing on many of the major philosophical and scientific figures of the era, including Empedocles, Alcmaeon, Anaxagoras, Democritus and Aristotle—all of whom incorporated optical technologies into their theoretical frameworks. To this end, I will establish what could be called a technological history of vision. That being said, many of the implements employed as cognitive tools in this tradition were present throughout all eras of antiquity. As a consequence, it would be inappropriate to impose a narrative of invention and progress. Instead, I will illustrate how thinkers used technologies in their explanations according to which particular moment in the process of vision they were considering, sometimes even combining analogies to explain different stages in the complex process of sight. In other words, I will examine how theorists utilized both *competing* and *layered* technological heuristics to understand how we see.

In addition, investigating ancient optical theories can highlight another aspect of the relationship between technology and theory-formation—an aspect that will form a considerable part of the next two chapters. It concerns the fact that it is unclear whether we can consider vision a single physical process. When we look at the world, not only can we see light, darkness, colours, shapes, images, objects, things and people, but we can also see distance, magnitude and motion. Sight is simply a compound experience. When ancient authors talk about 'vision,' they can therefore be referring to one, several or many of these aspects. They are rarely—if ever—talking about them all. So-called 'theories of vision' can thus be explaining different things at different times. To state this a different way, vision as a target fieldof explanation is a contingent construction. Its operational definition expands and contracts.

Expansion arises for two main reasons. On the one hand, natural philosophers can simply pay attention to more of vision's features, incorporating colour, images, depth and light into their explanations. On the other hand, light and sight interact with various materials, creating observations that supplement what could be called bare vision. Because vision is not a fixed phenomenon, however, incorporating these experiences can change not only the parameters of explanation, but also the operational definition of sight itself. For instance, some thinkers might consider it superfluous to discuss how oars appear to bend in water, or how bright-coloured textiles cast a hue on surrounding objects. Others, however, will consider these crucial components of vision's essence.

As can be imagined, optical technologies play a large part in providing access to these supplemental appearances—whether in the form of a simple lamp aiding sight at night, or complex, curved mirrors displaying funhouse-style reflections. This is not to insist that those who focus on different aspects of vision experience sight in completely incommensurate ways or that they lose access to alternative features outright, merely that in choosing what to explain, theorists become selectively myopic, as it were, even if only temporarily. Ancient optical theorists do not catalogue and classify all the aspects of vision and then look for an explanation that satisfies all these observations; they address certain aspects and not others. In the process, their theories delineate and thus partially construct the very phenomenon they are attempting to explain.

It is complicated to unpack and articulate all the motivations behind such a selection. In general, however, we can say that ancient theorists address the aspects of vision that (they believe that) they can explicate. In other words, they let their cognitive tools determine which elements of vision they will consider to be its essential features. Certain aspects are thereby highlighted, while others are neglected. Potentially troubling factors are left aside. Earlier, I called this process cognitive focus. Many of the cognitive tools responsible for this type of focus stem from larger philosophical programs, and thinkers derive many aspects of their optical models from these broader philosophical commitments—whether to four-element or atomic theories of matter. At the same time, just as we saw in the previous two chapters, there is also a scientific reflex to reach for man-made implements to make nature comprehensible. As a result, many cognitive tools are drawn from the same optical technologies that provide access to new visual phenomena. Optical technologies thus play two key and related roles: 1) by creating certain parts of the visual experience, they implicitly determine what counts as 'vision' as a scientific phenomenon; and 2) they provide heuristics to conceptualize the mechanisms of vision itself. These two roles mutually support each other. As a consequence, vision as a concept is not simply a contingent construction; it is—at least in some of it aspects—a technologically contingent construction.

3.1 Cognitive Attraction and Empedocles' Lamp

Ancient natural philosophers were fascinated by both the mechanisms and epistemology of sight. Whether they articulated a physical model of the eyes or asked if we can base knowledge on our senses, almost every major philosophical figure of the ancient world provided some account of visual perception. Because there are so many different theories, however, scholars often rely on a simple explanatory rubric to categorize the various models, dividing ancient explanations into three types: 1) intromissionist theories (we see by means of something *entering* the eye); 2) extramissionist theories (we see by means of something *exiting* the eye); and 3) hybrid theories (we see by means of some mechanism compounded of the two).[250] Modern commentators are not without precedent in employing such categories. For instance, at one point during his investigation of vision, Aristotle applies a comparable set of

[250] For histories of vision that follow this approach, see Beare 1906; Lindberg 1976; Park 1997; M. Smith 1999: 23-34.

divisions to the theories of his predecessors,[251] and first century BCE astronomer Geminus characterizes earlier theories in precisely this tripartite way.[252] While there is merit in this approach, privileging solely these categories as a way of interpreting and articulating ancient optical theories has a few detrimental affects. Most importantly, it causes commentators—both ancient and modern—to shoehorn complex theories into one of these rigid classifications, even though few ancient accounts actually fit this schema. Ancient theories of visual perception are simply more complex than these three categories allow, and trying to understand ancient ideas exclusively through this rubric can cause considerable distortions.

Consider the following variants: we see by means of 1) a type of fire streaming from our eyes; 2) a contiguous linear projection extending to the visible object; and 3) a type of bullet-like projectile. Since all three explanations involve some substance leaving the visual organ, they would all qualify as extramissionist. Nevertheless, the physical, physiological and epistemological consequences are quite different in each case. If fire or light streams from the eye, we might ask why we cannot see in the dark. If contiguous rays project from the pupils 'like sticks,' we might ask whether these rays have any thickness, and, if so, how do they all fit into the eye. If the eyes send forth some projectile, how do these projectiles send information back once they exit the surface of the cornea? Each variation elicits slightly different questions and evokes different

---

[251] Arist. *Sens.* 437a18-438a25 categorizes his predecessors into 1) those who ascribe vision to fire (Empedocles and Plato) and 2) those who ascribe it to water (Democritus). He then switches to talk about extramissionist and hybrid theories before presenting his own viewpoint at *Sens.* 438a26-b15. Theophr. *De sens.* 1 adopts a different division: 1) those who ascribe vision to similarity [τῷ ὁμοίῳ] (Parmenides, Empedocles and Plato) and those who ascribe it to opposition [τῷ ἐναντίῳ] (Anaxagoras and Heraclitus).

[252] Gemin. *Frag Opt.* 24; cf. Aët. 4.13. In a similar fashion, [Eucl.] *Opt. proleg.* (A) juxtaposes the *eidola*-theory of the Atomists and Epicureans with the ray-theory of the mathematicians, seemingly adopting these two camps as paradigms of the intromissionist and extramissionist positions, respectively.

concerns. We would be well served, then, not to run such theories together under a single heading too quickly.

As with our investigation into respiration and blood delivery, the earliest Greek natural philosopher for whom we can reconstruct an adequate theory of vision is Empedocles, whose theory presents a prime example of the insufficiency of the above categories. On the one hand, he appears to propose both a pore-theory, whereby effluences enter *into* the eyes to cause visual perception. On the other hand, he also seems to propose an emanation-theory, whereby fire streams *from* the eye on the model of a lamp. These doctrines do not easily cohere, and, as we shall see, trying to join them together creates several difficulties. Yet, even having illustrated that Empedocles' doctrines are inconsistent, we can still ask why a tension emerges where it does. What I will argue is that Empedocles' adoption of the lamp is part of a larger scientific tendency to incorporate technological analogues even without clear philosophical purpose. That is, technologies are such powerful cognitive tools that often they are imported simply because they structure our experiences, not because they are needed to solve a particular problem. Earlier, I called this tendency cognitive attraction.

While Aristotle, Plato and the doxographical tradition all describe certain components of Empedocles' theory, Theophrastus' *De sensibus* presents the most detailed account. In it, Theophrastus articulates three separate aspects of Empedocles' model: 1) his general explanation of the senses; 2) his description of the eye's anatomy; and 3) his account of the eye's effluence-receiving pores:

> Ἐμπεδοκλῆς δὲ περὶ ἁπασῶν ὁμοίως λέγει καί φησι τῷ ἐναρμόττειν εἰς τοὺς πόρους τοὺς ἑκάστης αἰσθάνεσθαι· διὸ καὶ οὐ δύνασθαι τὰ ἀλλήλων κρίνειν, ὅτι τῶν μὲν εὐρύτεροί πως, τῶν δὲ στενώτεροι τυγχάνουσιν οἱ πόροι πρὸς τὸ αἰσθητόν, ὡς τὰ μὲν οὐχ ἁπτόμενα

διευτονεῖν, τὰ δ' ὅλως εἰσελθεῖν οὐ δύνασθαι. πειρᾶται δὲ καὶ τὴν ὄψιν λέγειν, ποία τίς ἐστι· καὶ φησὶ τὸ μὲν ἐντὸς αὐτῆς εἶναι πῦρ <καὶ ὕδωρ>, τὸ δὲ περὶ αὐτὸ γῆν καὶ ἀέρα, δι' ὧν διιέναι λεπτὸν ὂν καθάπερ τὸ ἐν τοῖς λαμπτῆρσι φῶς. τοὺς δὲ πόρους ἐναλλὰξ κεῖσθαι τοῦ τε πυρὸς καὶ τοῦ ὕδατος, ὧν τοῖς μὲν τοῦ πυρὸς τὰ λευκά, τοῖς δὲ τοῦ ὕδατος τὰ μέλανα γνωρίζειν· ἐναρμόττειν γὰρ ἑκατέροις ἑκάτερα. φέρεσθαι δὲ τὰ χρώματα πρὸς τὴν ὄψιν διὰ τὴν ἀπορροήν.

Empedocles says similar things about all [the senses] and asserts that perception occurs because [something] fits into the pores of each sense. Because of this he also says that the each sense is unable to discern the objects of the others, since somehow some of the pores happen to be too wide, and others too narrow for a given perceptible object.[253] And in this way some pass right through without touching, while others are wholly unable to enter. He also attempts to say what sort of thing the eye is, and he asserts that there is fire inside of it, and air and earth around this, through which the fire passes, since it is fine, *just like the light in lamps*. And he says that the pores of fire and water lie in alternation and that the pores for fire recognize white things and those for water recognize black things.[254] For each of these elements fit into their respective pores. The colours are carried to the eye on account of the effluence (Theophr. *De sens*. 7, emphasis mine).

From this passage, it seems at first that Empedocles proposes an intromissionist theory, insofar as he claims that all perceptions occur because thin 'effluences' [αἱ ἀπορροαί] flow from objects and enter into appropriate pores in the sense organs.[255] The same general mechanism allegedly functions for all the senses, and each sense only accepts a specific size of effluence, which prevents cross-stimulation. Although these pores are microscopic in nature, Empedocles' theory certainly derives its plausibility from the idea that we hear through the macroscopic orifices of our ears, we smell through the macroscopic orifices of our nostrils, and we taste through the macroscopic orifices of our

[253] Stratton 1917: 163, n. 23 notes that although αἰσθητόν means the perceptible object, Theophrastus is using the term loosely to refer to the effluence, rather than the object of sense from which the effluences flow.

[254] Long 1966: 261 suggests that Empedocles intended for there to be pores of air and earth as well, but he admits there is no evidence to support this claim.

[255] Theophr. *De sens*. 7-8; cf. DK 31 B 89.

mouths. Theophrastus claims that this general account applies to vision as well,[256] and Plato provides some independent corroboration of this in the *Meno*, where Socrates mentions that Empedocles ascribed vision to effluences fitting [ἁρμόττειν] into the pores of the eye.[257]

Not *all* effluences entering the sense-pores will necessarily trigger perception, however, since if this were the case, the theory would be unable to account for why small effluences do not cause perception when they pass into the pores of another sense organ (e.g. Empedocles would be unable to explain why we do not both see and hear the thinnest effluences).[258] Therefore, effluences 'fit' only insofar as they are precisely the same size as the pores, thereby touching [ἁπτόμενα] the sides as they pass through and triggering perception in the process. This is presumably what Socrates means by stating that for Empedocles only the effluences that are "commensurate to sight" [ὄψει σύμμετρος] are visible.[259]

As for *what* the eye perceives, pores are divided into two types, those for fire, which recognize white, and those for water, which recognize black.[260] Since the πόροι

[256] Touch does not fit easily within this paradigm; Theophr. *De sens.* 20 criticizes Empedocles on this point.

[257] Pl. *Meno* 76c7-d5; cf. Aët. 4.9.6.

[258] It is also unclear how the same elements can trigger multiple senses, since if fire fits into the pores of more than one sense, there must one size of fire for vision, one for taste, one for hearing, etc.

[259] Pl. *Meno* 76d4.

[260] Theophrastus' description uses genitives, namely that these are pores *of* fire and *of* water [τοῦ τε πυρὸς καὶ τοῦ ὕδατος], but it is clear that their main function is to be pores *for* fire and *for* water, even if they are also made of fire and water. Ierodiakonou 2005: 10, n. 15, 29 notes that this indicates that Empedocles ascribes colour only to these two elements and not to air and earth (*pace* Prantl 1849: 127-28; Kranz 1912; Cherniss 1935: 217, n. 280; Seigel 1959: 152-3; Bruno 1977: 56-57; cf. n. 263 below). The difficulty comes from interpreting a key passage:

γαίηι μὲν γὰρ γαῖαν ὀπώπαμεν, ὕδατι δ' ὕδωρ,
αἰθέρι δ' αἰθέρα δῖον, ἀτὰρ πυρὶ πῦρ ἀίδηλον,
στοργὴν δὲ στοργῆι, νεῖκος δέ τε νείκεϊ λυγρῶι.

are passageways and thus provide transit for something,[261] it makes sense to presume that the effluences pass through into the interior of the eye, and the eye as a whole reconstructs an object's colour based on the ratio of water and fire particles that reach it. I take this to be the force of the short fragment: "one sight arises from both" [μία γίγνεται ἀμφοτέρων ὄψ].[262] Empedocles' explanation takes for granted the common Greek idea that all colours fall somewhere on the spectrum between white and black (or light and dark), which form not only the poles, but also the constituent elements of colour.[263] Regardless of the specific details, however, this appears unquestionably to be some type of intromissionist theory.

> By earth we see earth, by water we see water,
> Divine aether by aether, and by fire destructive fire,
> And affection by affection, and also strife by painful strife (Empedocles DK 31 B 109).

Most scholars agree that Empedocles is here using 'seeing' metaphorically to mean 'knowing,' which is necessary to make the passage cohere with his belief that only water and fire have colour. The case for this interpretation becomes especially strong if we accept M.R.Wright's 1981 ordering of the fragments, which makes this passage a description of the composition of blood, which is itself responsible for thinking; cf. Sedley 1992: 26-29. Nevertheless, the conceptual similarity should at least leave open the possibility that we see 'like with like,' even if only water and fire participate in colour perception; cf. von Fritz 1953.

[261] Cf. Pl. *Meno* 76c8, which describes the effluences traveling through [πορεύεσθαι] the πόροι. That being said, in many other places, Empedocles uses πόροι as a general concept for 'receptive space,' especially in his discussions of mixtures at DK 31 B 3, 77, 78, 86, 89; cf. Longrigg 1967 for Empedocles' views on mixture.

[262] Emped. DK 31 B 88 = Arist. *Poet.* 1458a4. Aristotle provides no context for the passage, since he is only using it to demonstrate the poetic spelling ὄψ.

[263] Although there were multiple colour theories in antiquity, all of them contain a particular feature that is foreign to our modern models: ancient colour systems almost always consider black and white to be the two spectral poles, not, as we do, violet and red. Moreover, they also consider white and black to be the two constituent *elements* of colour; that is, not only do these theories presume that all other colours fall somewhere between these two opposite poles, situated somewhere on a scale between light and dark, but they believe that all colours arise from the actual mixture of black and white. Different thinkers propose different ratios, but all basically agree on this fundamental point, including Empedocles (DK 31 A 69a = Theophr. *Sens*. 59), Parmenides (DK 28 B 8.38-41), Anaxagoras (DK 59 B 4; cf. Theophr. *Sens.* 59), Plato (*Tim.* 67c4-68d7), Aristotle (*Sens.* 439b15-440b25, 442b21-29—who describes five basic colours produced by mixing black and white; cf. *Mete.* 374a4-375a29) and the pseudo-Aristotelian author of *De coloribus* ([Arist.] *Col.* 791a1-792a5—although this author adds the yellow of flame as a third elemental colour). Theophr. *De sens.* 59 even claims that along with Empedocles "the rest only said this much, that white and black are the elements, while the other colours result when these two are mixed" [οἱ δὲ ἄλλοι τοσοῦτον μόνον, ὅτι τό τε λευκὸν καὶ τὸ μέλαν ἀρχαί, τὰ δ᾽ἄλλα μειγνυμένων γίνεται τούτων]. For discussions of this colour scale, see Hahm 1978; Ferrini 1999; Ball 2001: 15; Pastoureau 2001: 13-32.

In his short summary above, however, Theophrastus has provided another physiological feature of Empedocles’ eye that complicates this picture: the eye contains fire at its centre. Despite the fact that Empedocles has proposed a distinctly intromissionist theory of vision, he states that this fire streams *from* the eye through the air and earth membranes, “just like the light in lamps” [καθάπερ τὸ ἐν τοῖς λαμπρῆρσι φῶς]. Aristotle preserves the lamp comparison to which Theophrastus is referring in its entirety, so we can examine it a bit more closely:

> ὡς δ’ ὅτε τις πρόοδον νοέων ὡπλίσσατο λύχνον
> χειμερίην διὰ νύκτα, πυρὸς σέλας αἰθομένοιο,
> ἅψας παντοίων ἀνέμων λαμπτῆρας ἀμοργούς,
> οἵ τ’ ἀνέμων μὲν πνεῦμα διασκιδνᾶσιν ἀέντων,
> φῶς δ’ ἔξω διαθρῷσκον, ὅσον ταναώτερον ἦεν,
> λάμπεσκεν κατὰ βηλὸν ἀτειρέσιν ἀκτίνεσσιν·
> ὣς δὲ τότ’ ἐν μήνιγξιν ἐεργμένον ὠγύγιον πῦρ
> λεπτῆισίν <τ’> ὀθόνησι λοχάζετο κύκλοπα κούρην,
> <αἳ> χοάνησι δίαντα τετρήατο θεσπεσίῃσιν·
> αἳ δ’ ὕδατος μὲν βένθος ἀπέστεγον ἀμφιναέντος,
> πῦρ δ’ ἔξω διίεσκον, ὅσον ταναώτερον ἦεν.
>
> Just as when someone considering a journey forward
> through the stormy night equips himself with a lamp
> —the brightness of blazing fire—having fixed grates on it,
> which protect from all sorts of winds and scatter the breath of the winds as they blow. Light leaps through, insofar as it is thinner,
> and shines over the threshold with unyielding rays.
> In this way at that time she brought forth the primeval fire, bound in membranes, the round pupil in fine-woven cloths,
> which kept out the depths of the water flowing round,
> but the fire passed through to the outside, insofar as it was thinner (Emped. DK 31 B 84 = Arist. *Sens.* 437b26-438a3).[264]

[264] Sedley 1992 places “from which Aphrodite put together unyielding eyes” [ἐξ ὧν ὄμματ᾽ ἔπηξεν ἀτειρέα δῖ᾽Ἀφροδίτη] (DK 31 B 86) directly before the lamp simile, thus making Aphrodite the agent of the construction. M.R.Wright 1981: 126-127 and Inwood 1992: 249, fr. 100-103 interpose two related passages, but their order still upholds the same idea.

Although we may naturally think of a camp-style lantern, or perhaps a nautical oil lamp, Empedocles is picturing a lamp that is not encased in glass, but has simple perforated windscreens to protect it.

He therefore appears to be suggesting that the very interior of our eye is composed of fire, around which thin, semi-permeable membranes (perhaps of air and earth?) are wrapped. These perforated "grates" are in turn surrounded by some type of water. The membranes allow fire to pass through, but prevent water from flowing in. As simple as this description sounds, there are many questions it raises, including: 1) where is the water; 2) where is the fire; and 3) how does this anatomical model relate to the pore-theory that Theophrastus and Plato have already ascribed to Empedocles?

Let us start by addressing the location of the water. Because the simile describes a lamp whose grates protect its *interior* fire from the *external* air, it would be easy to assume that, for Empedocles, fire sits inside the eye, water sits outside of the eye, and membranes separate the two. In this case, we could thus potentially identify the water with what we would call the lachrymal fluid, since this liquid occupies roughly this external position. If this were so, however, Empedocles would certainly be stretching the poetics of "the *depths* of the water flowing round" [ὕδατος ἀμφινάοντος βένθος], since he would be using it to refer to a thin layer of moisture on the surface of the eye.[265] Moreover, "depths" more naturally suggests the eye's deeper, *interior* fluid, since water is dark—especially deep water[266]—and the blackness glanced through the pupil displays

[265] Sedley 1992, n. 10 likewise notes that this is an "extravagant term for a thin film of water," although he still takes the referent to be the lachrymal fluid.

[266] See DK 31 B 94, where Empedocles describes darkness in the 'depths of the river' [*niger in fundo fluvii color*]; cf. [Hippocr.] *Carn.* 17.10-14, which also links the blackness of the eyes to their watery depth. Similarly, Arist. *Gen. an.* 779b15-20 attributes the colour of the eyes to the amount of fire and water in them, i.e. blue-grey eyes are fiery, while darker eyes are watery. This appears to be separate from the

this characteristic, while the eye's gleaming white surface does not. On this reading, the water sits inside the eye, but still "flows around" an even more interior pocket of fire.[267] If this were not the case, Empedocles would have completely ignored the fact that eyes exude moisture when you cut them open, since in placing water only on the surface of the eye, he would have totally omitted water in his physiological description.[268]

Interpreting the passage in this way potentially provides a way to bring together the lamp comparison and some aspects of the pore theory, since the watery depths could be where the water pores lead, while the lamp-like fire could be an interior core to which the fire pores lead. Yet, even if we should imagine Empedocles' physiology of the eye in this way—as I think is most likely—his comparison is still somewhat odd, since the external air of the simile is identified with water *inside* of the eye, and the open air is not actually represented in the comparison at all.[269] Nevertheless, the membranes would still fulfill their two functions, both: 1) to keep the internal water from quenching the internal fire; and 2) to let the fire pass through into the exterior air. These 'windscreens' could easily be mistaken for pores.[270]

Having reconstructed at least a plausible model for Empedocles' explanation, we might still ask how these physiological descriptions relate to the anatomy of an actual

---

Hippocratic, medical tradition, which discusses eye-colour in relation to glaucoma and cataracts, see [Hippocr.] *De visu* 1-2, *Prorrh.* 2.20; cf. Craik 2006: 49-55.

[267] For such a view, see Panzerbieter 1845 no. 111 coll. 883-4; Diels 1884: 354; Burnet 1920: 248; Lackenbacher 1913: 39-40; O'Brien 1970. As an extension of this idea, both Lloyd 1966: 326 and Ierodiakonou 2005: 26, n. 39 suggest that the membranes prevent water from *exiting* the eyes and that fire and water are both contained within the eye. This cannot be true unless the two substances are separated, lest the grate-like membranes serve no purpose.

[268] Cf. Arist. *Sens.* 438a17-20 for this objection.

[269] This is the case even if we presume that the air of the simile is supposed to be the lachrymal fluid.

[270] *Pace* Alex. Aphr. *In de sens.* 23.8-24.9, who claims that fire passes through the membranes because of their fineness, not because of any pore-like openings. This, however, is to disregard the grate-analogy.

eye. This question is especially difficult to answer, since no part of the eye offers easy identification as Empedocles' "internal fire." Longrigg suggests that Empedocles is talking about the lens,[271] but Caston and Sedley have both rejected this position, pointing out that very little was known about ocular anatomy at the time, since systematic dissection was not yet being practiced.[272] Yet, these two scholars assume that because Empedocles does not know about the eye's interior parts, he must therefore be describing its *external* features, and they thus suggest that the fire represents the cornea. This is mistaken logic: just because Empedocles may not be familiar with the actual interior anatomy of the eye, does not mean that his simile does not *construct* it. Indeed, he hypothesizes that in some animals the interior fire sits in the centre of the eye, while in others, it rests closer to the surface [ταῖς μὲν ἐν μέσῳ, ταῖς δ᾽ἐκτὸς εἶναι τὸ πῦρ].[273] If he identified the fire with the cornea, this could not be the case, since it *always* rests on the surface. Therefore, Empedocles must be referring to internal features of the eye, but the lamp *predicates* these features; it does not explain them.

If this is the anatomical picture created by Empedocles' simile, we are left with many questions: how does the fire *exiting* through the membranes relate to the fire and water *entering* through the pores? Do they use the same passageways? How do they not impede each other? How does the fire exiting the pores not also cause visual perception,

[271] Longrigg 1976: 437 suggests that Empedocles might have arrived at this theory as a result of his own investigations into the physiology of the sense organs, perhaps influenced by Alcmaeon; cf. Millerd 1908: 83; Theophr. *De sens.* 26.

[272] Caston 1985:17-23; Sedley 1992: 20-26; cf. Lloyd 1975.

[273] Theophr. *De sens*. 8.

if it fits into these same passageways?[274] If not, does it require separate pores? Are there therefore *three* different sets of passageways? If this is the case, are there different types of fire, some of which cause perception, and some of which exit the eye? Scholars have attempted to address these problems in multiple ways, but to limited success. For instance, Ross, Taylor, Verdenius, Long and Sedley have all assigned different and separate roles to both sets of fire in the visual process,[275] but they leave many of the above questions unanswered and rely for too heavily on speculation with insufficient textual support. In fact, because attempts to combine these two aspects of vision have all been inadequate, others, including Cherniss, O'Brien and Ierodiakonou, have argued that the fire emanating from the eye only has anatomical significance and has nothing to do with the way the eye actually perceives.[276] As O'Brien puts it, the lamp simile was not

---

[274] Theophr. *De sens.* 13 makes same this objection. In this section Theophrastus asks whether the pores are empty or full. They cannot be completely empty, he argues, because Empedocles denies the existence of any void (cf. DK 31 B 13), yet they cannot be filled with the fire commensurate to them either, since that would cause us to perceive all the time.

[275] G.R.T. Ross 1906: 137-138 claims that the images entering the eye need to be illuminated by the internal fire, but his account does not take into account how fire would 'illuminate' water without being quenched. Taylor 1928: 280-281 argues that the effluences described by Theophrastus and Plato refer only to *colour* vision, whereas Empedocles' general theory is extramissionist—but this is again to fracture his theory without a great deal of textual support. Long 1966 suggests that vision occurs when the internal and external fires are in right correspondence, but this simply transforms Empedocles' theory into that of Plato's at *Tim.* 45b2-46a2; cf. O'Brien 1970. Verdenius 1948 argues that Empedocles has produced a physical model for an epistemological argument—that is, the lamp-fire is a psychic projection of our internal perceptions onto an external reality and thus actually represents a *mental* reflection whereby what we receive passively through the pores is turned into an objective reality. Along with being unduly speculative, Verdenius takes for granted that Empedocles is talking about reflection, for which there is no evidence. In contrast, Sedley 1992 contends that the fire somehow collects on the surface of the eye and mixes with the lachrymal fluid to produce a reflection, which he considers Empedocles' cause of vision. This turns Empedocles' theory into Alcmaeon's and does not account for the effluences *entering* the sense pores to cause perception.

[276] Cherniss 1935: 318, n. 106 claims that the fire only refers to the gleaming and "flashing" of the eyes; O'Brien 1970: 144 argues that Empedocles actually posits two separate groups of "funnels" in the eye, one for the entering fire and water effluences, and one for the fire that exits the eye. Ierodiakonou 2005 attempts to harmonize the two passages by proposing that the alternating pores for fire and water are situated in the membrane discussed in the lamp simile, but she assigns no role to the outward streaming fire in perception.

intended as a model for the *function* of the eye (which is explained by the pores), but only its composition.[277]

Perhaps the best evidence in support of this latter argument is that Aristotle himself hedges on whether Empedocles is really describing an extramissionist theory of vision when he presents the lamp simile, prefacing his assertion with the remarks that Empedocles merely "seems to one who considers it" [ἔοικε νομίζοντι] to ascribe vision to the fire leaving the eye.[278] And, as O'Brien has shown, when Aristotle uses this type of expression, it generally indicates that the interpretation that follows is somewhat less than a faithful representation of his predecessors' actual doctrines.[279] Moreover, Aristotle prefaces his portrayal of Empedocles as an extramissionist by stating that "sometimes [Empedocles] claims that vision works in this way [by the fire issuing from the eye], but other times by means of emanations from the things being seen" [ὁτὲ μὲν οὖν οὕτως ὁρᾶν φησίν, ὁτὲ δὲ ταῖς ἀπορροίαις ταῖς ἀπὸ τῶν ὁρωμένων].[280] The temporal distinction between the two ways of interpreting Empedocles' poem suggests that Aristotle himself does not view these two aspects as part of a unified doctrine. Empedocles' theory does not easily cohere. The lamp comparison creates a tension with the eye's pores, which otherwise establish the eye as a receptive organ.

---

[277] O'Brien 1970: 166; cf. Barnes 1982: 178: "Many scholars attempt to extract a theory of vision from it, but in fact the fragment means only to describe the structure of the eye." Similarly, Beare 1906: 20 and Millerd 1908: 84 remain skeptical whether any synthesis can be made between the simile and Empedocles' general explanation of perception.

[278] Arist. *Sens.* 437b24-25.

[279] O'Brien 1970: 142-43. He cites Arist. *Metaph.* 1042b11-15 [ἔοικε οἰομένῳ] and *Gen. an.* 724b34-725a1 [ἐοίκασιν οἰομένοις], which are both followed by rather liberal interpretations.

[280] Arist. *Sens.* 438a4-5.

So why does Empedocles use the lamp to model the eye? Is it just a poorly chosen analogy? Of course, no definitive answer can be offered, but some scholars point to the metaphorical conflation of the eye and the sun within the poetic tradition.[281] Although this could certainly be part of the motivation, Empedocles does not compare an eye to the sun; he compares it to a *lamp*. Others scholars, such as Millerd, offer the idea that the conflation is simply "natural."[282] I would like to interrogate this a little more. What is at stake in claiming that this comparison is simply "natural"? Why is an eye naturally like a lamp? I would like to suggest that Empedocles employs his simile because the lamp is a piece of optical technology. That is, adopting the lamp as a cognitive tool is "natural" to a certain extent, but only insofar as Empedocles is implicitly structuring his experience of vision based on his interactions with the technologies around him—however basic those might be. He incorporates the lamp because a lamp is a tool that helps him to see. The lamp makes light manipulable in the physical realm, and thus makes the eye comprehensible in the cognitive realm. Support can be gained from the fact that Empedocles has used technological implements in his accounts of both the ears (a bell) and the lungs (*clepsydra*).

As we saw in the last chapter, however, once the analogy is employed, it becomes an active heuristic, shaping elements of Empedocles' physical and physiological theories. We can see this in two ways. First, on a basic level, even if other comparisons might also suggest this feature (such as the conflation with the sun), the lamp suggests the idea that fire streams from the eye. It is not something that Empedocles would assume without

[281] For example, O'Brien 1970: 144-145, where he gives the example of Aesch. *Prom.* 356 and Theocr. *Id.* 24.18-19.

[282] Millerd 1908: 84.

some heuristic (even a commonly accepted one). Second, even though this fire cannot be an active agent in visual perception according to the pore-theory, Empedocles nevertheless employs it to explain why some animals can see better at night than others. He holds that animals with *less* internal fire in their eye see better during the daytime, since the external light augments it to provide a balanced amount [ἐπανισοῦν], whereas at night the excessive external darkness (i.e. water) overwhelms the small amount of fire in the eye. Conversely, animals with *more* internal fire see better during the night, since the internal fire "fills up" the lack of external fire [ἐπαναπληροῦσθαι], whereas during the day it "augments" the external fire [ἐπαυξάνεσθαι], and both "plasters over" [ἐπιπλάττειν] and "cuts off" [καταλαμβάνειν] the pores of water.[283] As a consequence of these arguments, those who insist that the lamp simile only has 'anatomical,' rather than physiological significance cannot be wholly correct, since Empedocles incorporates the internal fire into his explanation of the mechanics of night-vision. The lamp cannot *solely* concern the eye's composition, since the amount of fire in the eye directly affects the acuity of visual perception.

Once invoked, the lamp becomes an active cognitive tool, ready-at-hand for any potentially relevant explanation. The context in which Empedocles employs this heuristic amplifies this assertion, since he presumes that the eye works like a lamp precisely when an actual lamp would be used. In other words, he can see at night because of an actual tool; then, when he needs to explain night vision, he reaches for that same implement. His cognitive focus is directed to a particular feature of vision, and it pulls the lamp, with its material specificity, into his construction of both the anatomy and function of the eye.

[283] Theophr. *De sens*. 8; cf. *De sens.* 18; Arist. *Gen. an.* 779b12-20.

3.2 Cognitive Focus and the Mirror

Although the lamp plays a unique role in Empedocles' physiology of the eye, it did not monopolize ancient ocular models. Instead, perhaps the most influential material technology in the history of ancient visual theories was the mirror. Mirrors were so crucial to mathematical optics that an entire genre of catoptrical texts emerged to explain the various images that appear in them.[284] Reflection also fascinated philosophical authors, and it often seems necessary for any theory of vision to provide both an explanation of eyesight and a corollary explanation of the behaviour of images in mirrors. For instance, the doxographical tradition indicates that virtually every ancient theorist who deals with vision also discusses reflection, including Empedocles, Leucippus, Democritus, Epicurus and the Pythagoreans,[285] and numerous other authors follow the same practice. For instance, in the *Timaeus*, Plato's stranger follows an explication of vision—which articulates how the demiurge constructed the body and placed fire in the eye—by turning immediately to an explanation of mirrors.[286] Likewise, Lucretius begins to explain eyesight, only to provide an account of reflection in the midst of it.[287]

In antiquity, mirrors became so closely associated with vision that they were often viewed as part of the same essential phenomenon. For many ancient thinkers, reflection was far more than a secondary optical behaviour; mirrors were an integral part of what it

[284] Attested catoptrical texts include contributions from Euclid, Archimedes, Diocles, Hero, Ptolemy and Anthemius. These texts provide mathematical explications of sightlines, attempt to answer why concave mirrors can start fires and give instructions on how to construct funhouse-style reflections. For a survey of catoptrical texts and their geometrical interrelations, see LeJeune 1957; cf. Knorr 1983; Jones 2007.

[285] Aët. 4.14; cf. Alex. Aphr. *Mantissa* 133.4-6, where he attacks the inability of the Stoics' *tonos*-theory to explain reflections in mirrors; cf. Alex. Aphr. *In de sensu* 25-26.

[286] Pl. *Tim.* 46a3-c5; cf. *Tht.* 193c6-d2.

[287] Lucr. *DRN* 4.269-323.

meant to talk about sight. In other words, vision's operational definition expanded to include reflection as one of its essential aspects. Perhaps as a result, there was a powerful tendency to conceptualize vision itself as a type of reflection. Multiple theorists promoted this idea while using actual reflective implements to understand the mechanism of the eye. In this section, I will examine this tendency, while demonstrating that by using this heuristic, Greek optical theorists incorporated actual material features of ancient Greek mirrors into their explanations. They based their assumptions about the nature of reflection and, by extension, the nature of vision, on the particular optical technologies around them.

Alcmaeon, the earliest thinker whom Theophrastus addresses in *De sensibus*, ascribes vision to reflection. His theory of vision—or at least the portion that has been preserved—is quite succinct. He says that "the eyes see by means of the water surrounding the eye" [ὀφθαλμοὺς δὲ ὁρᾶν διὰ τοῦ πέριξ ὕδατος].[288] This moisture allows the eye's surface to "reflect back" [ἀντιφαίνῃ] by its "gleaming and diaphanous nature" [τῷ στίλβοντι καὶ τῷ διαφανεῖ],[289] and he proposes that we see "according to this reflection of the diaphanous" [κατὰ τὴν τοῦ διαφανοῦς ἀντίλαμψιν].[290] At the end of the fifth century BCE, the Hippocratic author of *Fleshes* claims something quite similar, asserting that the eye sees by "shining back":

[288] Theophr. *De sens.* 26. Beare 1906: 11 suggests that this water is inside the eye, but if this were the case, it is unclear how the eye would reflect back an image.

[289] Wachtler 1896: 49 claims that the gleaming refers to the eye's fire, while the transparency refers to the eye's water. Beare 1907: 11, n.3 argues that στίλβειν is more regularly used of water's gleam than the glint of fire.

[290] Alcmaeon, DK 24 A 10 = Aët. 4.13.12. I here follow Diels suggestion in emending the MS entry ἀντίληψιν, apprehension, to ἀντίλαμψιν, reflection, which brings the passage in line with Theophr. *De sens.* 26; see *Dox. Gr. prol.* 223, 404.

> τούτῳ γὰρ τῷ διαφανεῖ ἀνταυγέει τὸ φῶς καὶ τὰ λαμπρὰ πάντα· τουτέῳ οὖν ὁρῇ τῷ ἀνταυγέοντι· ὅ τι δὲ μὴ λαμπρόν ἐστι μηδὲ ἀνταυγεῖ, τουτέῳ οὐχ ὁρῇ·
>
> For light and all bright things shine back by this transparency. And so one sees by this reflecting. And whatever is not bright and does not shine back, one does not see by that ([Hippocr.] *Carn.* 17.8-10 L 8.606 = *De loc. in hom.* 2 L 6.278).

Anaxagoras too proposes that "the eye sees by reflection in the pupil" [ὁρᾶν μὲν γὰρ τῇ ἐμφάσει τῆς κόρης],[291] and Diogenes of Apollonia likewise attributes vision to reflection, or "immanent appearance" [ἔμφασις][292] but adds the stipulation that reflection only "causes perception when it is mixed with the internal air" [ταύτην δὲ μειγνυμένην τῷ ἐντὸς ἀέρι ποιεῖν αἴσθησιν].[293] For his part, Democritus maintains that vision is caused by a reflection in the eye [τὴν ἔμφασιν τὴν εἰς τὴν ὄψιν], although, as we shall examine in the next section, he understand this reflection in a unique way as part of his broader effluence-theory.[294] Nevertheless, versions of reflection-theory were so widespread in classical antiquity that Theophrastus claims that "some opinion concerning reflection is common; for basically everyone understands seeing in this way, namely by reflection occurring in the eye" [περὶ δὲ τῆς ἐμφάσεως κοινή τίς ἐστιν ἡ δόξα· σχεδὸν γὰρ οἱ πολλοὶ τὸ ὁρᾶν οὕτως ὑπολαμβάνουσι διὰ τὴν γινομένην ἐν τοῖς ὀφθαλμοῖς ἔμφασιν].[295] Although Theophrastus is occasionally hyperbolic in attributing

---

[291] Theophr. *De sens*. 27.

[292] We should note that ἔμφασις literally means "appearing in" and does not necessarily connote the act of bouncing back that we associate with reflection. Nevertheless, it is still used to describe the behaviour of mirrors. Distinguishing between these two conceptions of reflection is crucial for understanding Democritus' theory of vision; see below.

[293] Theophr. *De sens*. 39, cf. 47. For an account of Diogenes' theory, see Beare 1906: 41-42.

[294] Theophr. *De sens.* 80; see below for a longer discussion of Democritus' account.

[295] Theophr. *De sens.* 36.

a common idea to a multitude of theorists,[296] in this instance he is marking the real conceptual power that reflection held as a way to think about sight.

Why was this tendency so common? Why, to borrow our previous vocabulary, did it seem so 'natural'? On the one hand, the idea must have come from the fact that the eye does, in fact, produce a tiny reflection on its surface. When you look into someone else's eyes, you can see a small image of yourself looking back. As Socrates mentions in the *Alcibiades*, the pupil [κόρη] is so-named precisely because it reflects back a small "puppet" [κόρη], "just as in a mirror" [ὥσπερ ἐν κατόπτρῳ].[297] Therefore, reflection-theory must have been derived in part from a basic empirical observation. Yet, noticing this effect and considering it the key component of the eye's operational mechanism are two different things.[298] The pupil also dilates and contracts (albeit less conspicuously), and reflection-theory has nothing to say about this. Thus, even if actual observations are responsible for noting the eye's capacity to reflect, we can still ask why this behaviour was deemed to be important, while others were not. In other words, why did theorists' cognitive focus fall on this particular feature?

Quite simply, thinkers gave causal weight to this surface reflection because the mirror was their optical technology *par excellence*. Just as Empedocles incorporated the lamp into his physiology because lamps are tools that augment sight, theorists attributed a

---

[296] Although the theory was clearly quite popular, we can take οἱ πολλοί to be a bit hyperbolic, especially since Theophr. *De sens.* 37 says the same thing about the number of people who believe the eye to be composed of fire. By comparison, Arist. *Sens.* 437a23-24 claims that everyone makes the eye out of fire, but then goes on to mention multiple people who do not share this belief; cf. Alex. Aphr. *In de sens.* 15, I, 5-14, who notes this inconsistency. Theophrastus therefore seems to be continuing what could be considered a tradition of hyperbole on this subject.

[297] Pl. *Alcib. I* 132e7-133a5.

[298] For instance, Arist. *Sens.* 438a5-9 agrees with Democritus that an ἔμφασις appears in the eye, but argues that this neither occurs because the eye is made of water, nor is itself the cause of vision. Rather, this reflection is merely a passive activity, an ἀνάκλασις that happens because the eye is smooth [λεῖον].

causal role to reflection because mirrors are tools that manipulate light. This prototypical optical technology highlighted reflection in the eye as a phenomenon of potential significance. As a corollary, the analogic extension of the mirror to the eye must have been facilitated by the fact that mirrors at that time were almost exclusively round.[299] The most common form of reflective implement were hand held 'disc mirrors' with a handle or base providing a cradle for a round polished surface, but even handle-less 'compact-style' mirrors were generally circular. The similarity in shape between ancient mirrors and the pupil must have strengthened the already compelling idea that reflection was the eye's active mechanism.

More than shape, however, several thinkers seem to have incorporated aspects of the actual material composition of Greek mirrors into their assumptions about the nature of reflection and the physical process of vision. Anaxagoras provides a good example of such a tendency, and Theophrastus provides a summary of his doctrine:

> Ἀναξαγόρας δὲ γίνεσθαι μὲν τοῖς ἐναντίοις· τὸ γὰρ ὅμοιον ἀπαθὲς ὑπὸ τοῦ ὁμοίου. καθ' ἑκάστην δ' ἰδίᾳ πειρᾶται διαριθμεῖν. ὁρᾶν μὲν γὰρ τῇ ἐμφάσει τῆς κόρης, οὐκ ἐμφαίνεσθαι δὲ εἰς τὸ ὁμόχρων, ἀλλ' εἰς τὸ διάφορον. καὶ τοῖς μὲν πολλοῖς μεθ' ἡμέραν, ἐνίοις δὲ νύκτωρ εἶναι τὸ ἀλλόχρων, διὸ ὀξυωπεῖν τότε. ἁπλῶς δὲ τὴν νύκτα μᾶλλον ὁμόχρων εἶναι τοῖς ὀφθαλμοῖς. ἐμφαίνεσθαι δὲ μεθ' ἡμέραν, ὅτι τὸ φῶς συναίτιον τῆς ἐμφάσεως· τὴν δὲ χρόαν τὴν κρατοῦσαν μᾶλλον εἰς τὴν ἑτέραν ἐμφαίνεσθαι.
>
> Anaxagoras [said that vision] occurs because of opposites; for the similar is not affected by what is similar. And he attempts to enumerate this according to each sense separately. *On the one hand, he says that seeing occurs by reflection in the pupil; on the other hand, he says that reflection does not occur in what is the same colour, but only in what differs*. And for most animals this differing colour takes place in the day, but for some it takes place at night, for which reason they see sharply at that time. And night is simply more dissimilar to the eyes. Things are reflected during the day, because light is a concomitant cause of reflection. *And the stronger*

[299] For surveys of Greek mirrors, see Forbes 1966; Congdon 1981; Lamb 1968: 125-129; Charbonneaux 1958: 29-32; cf. n. 308 below.

colour is reflected in the weaker (Theophr. *De sens*. 27, emphasis mine).[300]

As Theophrastus frames it, Anaxagoras' arguments about vision result from his larger explanations of perception in general, insofar as he attributes all sensations to alteration by opposites.[301] He appears to have provided greater justification for this idea, and Theophrastus continues on to describe it:

> τὸν αὐτὸν δὲ τρόπον καὶ τὴν ἁφὴν καὶ τὴν γεῦσιν κρίνειν· τὸ γὰρ ὁμοίως θερμὸν καὶ ψυχρὸν οὔτε θερμαίνειν οὔτε ψύχειν πλησιάζον οὐδὲ δὴ τὸ γλυκὺ καὶ τὸ ὀξὺ δι' αὐτῶν γνωρίζειν, ἀλλὰ τῷ μὲν θερμῷ τὸ ψυχρόν, τῷ δ' ἁλμυρῷ τὸ πότιμον, τῷ δ' ὀξεῖ τὸ γλυκὺ κατὰ τὴν ἔλλειψιν τὴν ἑκάστου· πάντα γὰρ ἐνυπάρχειν † ἐστὶν ἐν ἡμῖν.
>
> [Anaxagoras says that] touch and taste discern in the same way; for an object does not warm or cool something that is of the same warmth or coolness as it, even when they are brought near; the sweet or sharp do not recognize themselves through their [same qualities]; rather, the cold discerns by the hot, the potable by the brackish, and the sweet by the sharp, according to the lack of each. For he says that all things exist in us (Theophr. *De sens*. 28).

In general, Anaxagoras treats perception as an act of alteration, and because he holds that "like" can only be affected by what is "unlike," he ascribes all perceptual change to oppositional pairs. For vision in particular, these oppositions must arise between colours, and, as part of this idea, he claims that stronger colours are especially reflected in weaker colours.

When we think of reflection, we presumably think about how images interact with our colourless, metal-backed glass mirrors. Mirrors of this type are found in almost every bathroom and produce extremely high quality and (we would say) *accurate* reflections.

[300] Cf. Theophr. *De sens.* 37.

[301] This fits Theophrastus' general framework under which his predecessors ascribe perceptions to either similarity or dissimilarity; cf. Theophr. *De sens.* 1. Still, as part of his doctrine of perception as alteration-by-opposition, Anaxagoras argues that all perceptions are accompanied with pain; to my mind, this suggests that in this instance Theophrastus is not imposing his categories without justification; cf. Theophr. *De sens.* 29.

Insofar as this forms our technological environment, I would surmise that most people do not assume that reflection only occurs when objects are of a colour different from that of the mirror. This *cannot* be our assumption, since for us mirrors *qua* mirrors do not have a colour. In fact, it is precisely by being colourless that our mirrors embody the concept of reflection. In this way, accurate reflection and colour-contrast are antithetical. How, then, are the concepts of vision-by-reflection and vision-by-contrast compatible, let alone so intuitive for Anaxagoras? What are the cognitive tools that make this assumption 'natural'?

Once again, insight can be gained by placing these ideas within the material and technological context of Anaxagoras' time, especially since Greek mirrors of the fifth and fourth centuries BCE were not the clear, colourless surfaces that we use today. Our metal-backed glass mirrors were unknown in antiquity. Instead, reflective surfaces, including those of the disc mirrors described above, were made of many different materials, including copper alloy,[302] gold,[303] silver,[304] tin, dark glass,[305] obsidian[306] and coloured gemstones.[307] The most common material by far, however, was bronze.[308] Even

---

[302] Plin. *NH* 33.45.130; 34.48.160.

[303] Plin. *NH* 33.45.130; cf. Eurip. *Hec.* 924-925.

[304] Plin. *NH* 33.45.128, 130; 34.48.160.

[305] Plin. *NH* 36.66.193. For a discussion of glass burning mirrors, see below.

[306] Plin. *NH* 36.67.196.

[307] Plin. *NH* 37.25.97; cf. Theophr. *De lap.* 33. See Plin. *NH* 37.16.64 for the idea that Nero used an emerald as a mirror, although it seems more likely that he used it to soothe his eyes, since green gemstones were known for their healing power; cf. [Arist.] *Pr.* 31.19.959a24-38.

[308] Some of best examples of reflective implements in Greece from *c.* 600-430 BCE are the so-called Caryatid mirrors, which are bronze mirrors with a female caryatid figure functioning as a base; cf. Congdon 1981; Lamb 1968: 125-129; Charbonneaux 1958: 29-32. Both the base and the reflective disc were cast in bronze, using a tin-copper alloy. Although we might presume that the ideal mirror would be one without colour—which would entail higher levels of tin—Congdon 1981: 21 points out that a metal analysis of one

though rigorous polishing would have created high-resolution reflections, a bronze surface is still not colourless.[309] St. Paul famously immortalized the poor quality of ancient mirrors by stating that we humans only know as though "through a glass, darkly" [βλέπομεν γὰρ ἄρτι δι᾽ ἐσόπτρου ἐν αἰνίγματι].[310] The comment concisely expresses a material reality where the majority of Greek mirrors were metal and far from what we would consider optical quality.

This technological context bears on Anaxagoras' assumption that stronger colours reflect in the weaker, since holding up a smooth bronze object to a smooth bronze mirror will indeed produce a weak, almost invisible image, while a vibrantly-coloured, purple object will be easy to see. From a modern perspective, such behaviour indicates that bronze mirrors are deficient and unable to produce an accurate likeness with respect to colour. Of course, Anaxagoras does not see this from our modern perspective. Instead, because his technological world, he takes colour-contrast to be a characteristic of reflection *qua* reflection. When Anaxagoras uses mirrors to understand vision, he thus thinks with his particular optical technologies and the characteristics that these surfaces display.

As with our other theorists, once Anaxagoras has adopted a technological heuristic, he mobilizes it to explain multiple features. To this end, he extends reflection-by-contrast to explain night vision, claiming that humans see better during the day

---

of the discs surfaces showed that it actually had *less* tin than in the base. Moreover, there is little evidence that Greek technicians of this period actually strove to produce colourless reflective surfaces. Similarly, the majority of Etruscan mirrors were also made of bronze. For a catalogue of these mirrors from the same and subsequent periods, see Nicholls 1993; Swaddling 2001; de Grummond 2007.

[309] Even in Ptolemy's day the most common material was bronze, although other metals were also used, including gold, silver, lead and tin, all of which lend varying degrees of colour to the reflections; cf. M. Smith 1996: 144, n. 121; cf. Forbes 1966. See also [Arist.] *Col.* 793a18-20, 793b30-32.

[310] Corinth. 1:13.12.

because our eyes are black, and daytime therefore light contrasts with them better.[311] For other animals, this contrast occurs at night.[312] Yet, despite these claims, all *pupils*—even those of animals with excellent night-vision—are certainly still dark. At most, we could perhaps assert that *some* nocturnal animals have larger apertures for their pupils, and as such their eyes gleam more when light shines on them. Even so, it seems unlikely that Anaxagoras is attempting to make sense of an actual empirical observation regarding different types of pupils. Rather, it is more likely that the technological heuristic and its embedded assumptions come first and only activate arguments in other areas. By explaining night vision in this way, Anaxagoras lets the material behaviours of Greek mirrored surfaces stand in for the actual physical mechanism of eyes. The optical technology around him thus begins predicating what eyes *should* look like, rather than explaining how they actually appear. Thus, by incorporating the behaviour of contemporary mirrors into his understanding of vision, he structures his account of ocular physiology on the contingencies of his technological environment.

3.3 Layered Heuristics: Democritus' Mirrors and Wax Tablets

Anaxagoras is not alone in extending the mirror heuristic to explanations of night-vision. Several thinkers to whom Theophrastus attributes reflection-based theories also explain night- and day-vision according to colour contrast, including both Diogenes and Democritus.[313] In so doing, Democritus in particular incorporates physical aspects of the

[311] Theophr. *De sens.* 36-37. In fact, Anaxagoras claims that most animals have better vision during the day for this reason.

[312] Theophr. *De sens*. 27.

[313] Theophr. *De sens*. 42, 50, 54.

mirror into his explanation of vision. Yet, his account also operates with a second technological heuristic: the wax tablet. In fact, as we shall see, he uses the latter to understand the former. Thus, in this section I will show that while technologies can often function as theories, acting as the bedrock of explanation, Democritus treats his own cognitive tool as something that needs to be interpreted: he uses the mirror to understand the surface of the eye, but uses a wax tablet as a second technological heuristic to understand how image-transfer can take place on the surface of a mirror. As a result, he attributes physical characteristics of both mirrors and wax to the eye, according to which step in the process of vision he is discussing. In other words, he operates with layered heuristics, the scientific version of a mixed metaphor, as it were.

A comprehensive and coherent account of Democritus' theory of vision has proven difficult for scholars to articulate. The doxographical tradition certainly contains many reports about the theories of vision proposed by the Atomists in general, and in broad strokes, these reports largely agree: the Atomists believe that thin effluences called "images" [εἴδωλα] are emitted by all objects, and vision occurs when these εἴδωλα reach the eye. As Diogenes Laertius puts it concisely, the Atomists believe that "we see according to the impact of images" [ὁρᾶν δ᾽ἡμᾶς κατ᾽εἰδώλων ἐμπτώσεις].[314] The problem with this tradition, however, lies precisely in the standardization of the doxographical reports, since they cover over the differences between Democritus, Leucippus, Epicurus and Lucretius and instead attribute a common theory to them all.[315]

[314] Diog. Laert. 9.44 = Taylor 6.44.

[315] For instance, Aët. 4.13 groups Democritus with Leucippus and Epicurus on the grounds that they all share the εἴδωλα theory. Alex. Aphr. *In de sensu* 24.14-26 lumps Democritus together with Leucippus, while *Mantissa* 134.28-136.28 critiques the more general group 'those who say seeing happens by εἴδωλα'; cf. *In de sensu* 31.19-29, 56.8-59.18; DK 67 A 29, 31. Bicknell 1968: 12-14 argues that

Grouping all of these theorists together overlooks several discrepancies, most notably the fact that Democritus may not have actually used the vocabulary of εἴδωλα in his primary explanation of vision. To be sure, he did use the term, but most instances occur while he is explaining how floating images can cause dreams that foretell the future.[316] For instance, although Thrasyllus reports that Democritus wrote a work called περὶ εἰδώλων, it is also listed with a second title, περὶ προνοίης, indicating that the content was more likely related to soothsaying, not eyesight.[317] Likewise, Aristotle reports that Democritus attributed prophetic dreams to εἴδωλα καὶ ἀπορροίας,[318] and a whole tradition survives that links these εἴδωλα to parapsychology, so to speak, including reports from Plutarch,[319] Sextus Empiricus,[320] Olympiodorus[321] and Cicero.[322] In some sense,

---

Alexander and Aëtius assimilate Democritus to the Epicurean view based on a misreading of Arist. *De an.* 419a16-18; see below for a discussion of the passage in question.

[316] Cf. Bicknell 1968, 1969; Burkert 1977: 103-104. Burkert 1977: 108 argues that Aët. 4.8.10 = DK 67 A 30 indicates that thought, not perception, relies on the penetration of the εἴδωλα. Similarly, Lucr. *DRN* 4.26-44 treats the *simulacra* as responsible for dreams, even before he makes them responsible for vision.

[317] There are a few pieces of evidence that suggest Democritus may have used the terminology of εἴδωλα in his theory of vision, but all are problematic. First, Theophrastus evinces some confusion as to why Democritus attributes vision to an "imprint" [ἡ ἀποτύπωσις], when he has already spoken of effluences and εἴδωλα in his work περὶ εἰδῶν. Thrasyllus includes no such text as περὶ εἰδῶν in his list of Democritus' works and instead lists περὶ τῶν εἰδώλων ἢ περὶ προνοίης, which, as mentioned above, was likely about prophesy (DK 68 B 10a = 578 Luria). In addition, Heraclides Ponticus wrote a work called περὶ εἰδώλων πρὸς Δημόκριτον (see *SA* 36/37), which was apparently about prophetic dreams; cf. Clem. *Protr*. 5.66.5 = *SA* 123; Aët. 4.9.6; cf. Gottschalk 1980: 97-98. Thus, Burkert 1977: 103-104 proposes to emend Theophrastus' text so as to refer to Democritus' treatise as περὶ εἰδώλων, not περὶ εἰδῶν. This would harmonize with the fact that in the next line, Theophrastus states that "the εἴδωλα *themselves* appear immanently" [αὐτὰ γὰρ ἐμφαίνεται εἴδωλα] and the use of the intensive pronoun would be perplexing if the term had not already been mentioned, but it would also lead us to believe that Theophrastus' confusion over the discrepancy between ἡ ἀποτύπωσις and εἴδωλα is disingenuous, and he is misapplying terminology properly belonging to prophesy and dreams to what Democritus has to say about vision; cf. Schneider 1821; Alfieri 1936: 144. Nevertheless, it is also possible that Theophrastus' confusion about these two terms could suggest that Democritus used an imprint-model in his explicit discussion of vision, while using εἴδωλα to talk about vision in other contexts. In contrast, Guthrie 1965: 443 and Barnes 1982: 175 argue that Democritus' preferred vocabulary for the effluences is δείκελα, although DK 68 B 123 alone uses this vocabulary.

[318] Arist. *De div. somn.* 464a6-14.

[319] Plut. *Quaes. Conv.* 8.10.2 = DK 68 A 77 = 476 Luria; cf. Plut. *Aem. Paul.* 1.4l.

however, it does not matter for our purposes, since despite the ambiguity as to whether Democritus used this particular vocabulary, it is still clear that he proposed an effluence-theory to explain vision.[323] Yet, at the same time, like his predecessors, he also held that vision was caused by reflection. Theophrastus states simply: "Democritus says that seeing occurs because of an effluence and a reflection in the eye" [ὁρᾶν δέ φησι διὰ τὴν ἀπορροὴν καὶ τῆν ἔμφασιν τὴν εἰς τὴν ὄψιν].[324] That being said, he explains this reflection in his own unique way.

For Democritus, the whole process of vision is more complex than a simple image appearing in the pupil. Rather, he holds that something must first occur in the intervening air. Theophrastus provides the details:

> ὁρᾶν μὲν οὖν ποιεῖ τῇ ἐμφάσει· ταύτην δὲ ἰδίως λέγει· τὴν γὰρ ἔμφασιν οὐκ εὐθὺς ἐν τῇ κόρῃ γίνεσθαι, ἀλλὰ τὸν ἀέρα τὸν μεταξὺ τῆς ὄψεως καὶ τοῦ ὁρωμένου τυποῦσθαι συστελλόμενον ὑπὸ τοῦ ὁρωμένου καὶ τοῦ ὁρῶντος· ἅπαντος γὰρ ἀεὶ γίνεσθαί τινα ἀπορροήν· ἔπειτα τοῦτον στερεὸν ὄντα καὶ ἀλλόχρων ἐμφαίνεσθαι τοῖς ὄμμασιν ὑγροῖς.
>
> [Democritus] attributes seeing to reflection, but he means something unique by it. For [he says that] the reflection does not arise first in the eye, but that the air between the sight and the visible object is imprinted,

[320] Sext. Emp. *Ad math.* IX.19 = DK 68 B 166.

[321] Olympiod. *Comment. in Plat. Phileb.* p. 242 Stallbaum (Taylor 1999, 168).

[322] Cicero associates εἴδωλα and parapsychology at multiple points, including *Ad fam.* XV.16.1 = DK 68 A 118, *De nat. deo.* I.38.105-110 = Luria 470. Similarly, Cic. *De div.* II.58.120 = DK 68 A 137 does not discuss εἴδωλα, but describes a similar idea; cf. Cic. *De div.* II.67.137 = Luria 474, *De div.* I.3.5 = DK 68 A 138. Cic. *De nat. deo.* I.12.29 = DK 68 A 74 also suggests that the εἴδωλα relate images of the divine; cf. *De nat. deo.* II.30.76 = Luria 472a; *De nat. deo.* I.43.120 = DK 68 A 74; Augustine, *Letter* CXVIII.27-8 9 = Luria 472a.

[323] Recently, Rudolph 2011 has asserted that Democritus held a unified theory that including both εἴδωλα and imprints. Her reconstruction is thoughtful, but ultimately unconvincing. I deal with her arguments more extensively in n. 325 below.

[324] Theophr. *De sens.* 80; cf. Arist. *Sens.* 438a5-7, where Aristotle states that Democritus was right when he said the eye was made of water, but wrong insofar as he considered vision to be an immanent appearance [οἴεται τὸ ὁρᾶν εἶναι τὴν ἔμφασιν].

> having being compressed both by the visible object and the one seeing it; for he says that some effluence arises from each thing. Then, because this air is solid and variegated in colour, it appears in the moist eyes (Theophr. *De sens.* 50).

The theory of vision proposed in this passage is complex, but clear in outline: a thin layer of effluence [ἀπορροή] is emitted from every object. This effluence does not reach the eye directly, but instead impresses an image of itself into the air between the object and the eye. The imprinted air somehow "shrinks" [συστελλόμενον][325] under the pressure of effluences from the object and pressure from the eye.[326] This condensed, imprinted air then impacts against the ocular surface and creates a reflection.[327]

[325] While Stratton 1917: 111 translates συστελλόμενον as "is compressed" (cf. Beare 1906: 26, Guthrie 1965: 443), Burkert 1977: 99-100 points out that both Theophrastus and Aristotle use the term in opposition to αὐξάνεσθαι, "to increase," and should thus mean "to shrink" or "to get smaller"; cf. Rudolph 2011: 70-71. Still, in agreeing with the translation of this term as 'shrink' does not indicate, as Burkert and Rudolph propose, that Democritus advocated a perspectival system of proportional reduction in line with the optical cone of rays projecting from the eye. Both Burkert and Rudolph use the fact that Democritus wrote a text called ἀκτινογραφίη as evidence that he also proposed a geometrical optics. Rudolph even suggests that these rays themselves produce the proportional pressure on the air-imprints, thereby shrinking them down according to the strict laws of perspective. In his fragments, however, Democritus only uses ἀκτῖνες to refer to light beams traveling from the sun and other light sources, not a projection from the eye, which is called an ὄψις. Thus, it is more likely that the text was about celestial illumination, especially since Thrasyllus lists it in a tetralogy devoted to astronomical concerns, including "Diagrams of the Heavens" [οὐρανογραφίη], "Diagrams of the Earth" [γεωγραφίη] and "Diagrams of the Poles" [πολογραφίη] (Diog. Laert. 9.48 = DK 68 A 33); cf. Webster 2014, n. 6. In addition, Theophr. *De sens*. 54 says "Although [Democritus] attempts to say how magnitudes and distances appear immanently, he does not provide an account" [τὰ δὲ μεγέθη καὶ τὰ διαστήματα πῶς ἐμφαίνεται, καίπερ ἐπιχειρήσας λέγειν οὐκ ἀποδίδωσιν]. To my mind, it seems unlikely that Democritus presented a mathematically refined optics aligned with his physical doctrines, and that both Theophrastus and Aristotle subsequently ignored it.

[326] Scholars have disagreed whether the pressure is exerted by an effluence that flows from the eye, or the eye itself, since Theophr. *De sens.* 50, quoted above, claims simply that the air is compressed by both "the thing seen" and "the thing seeing it" [συστελλόμενον ὑπὸ τοῦ ὁρωμένου καὶ τοῦ ὁρῶντος]. It seems most likely that he means the eye and object by these two terms, and not two effluences, since an effluence from the eye can compress an imprint, but does not properly see the object. At the same time, the fact that he states as justification for this claim that "some effluence always arises from everything" [ἅπαντος γὰρ ἀεὶ γίνεσθαί τινα ἀπορροήν] could suggest that effluences supply the pressure. Indeed, English 1915, Guthrie 1965: 442-443; Mugler 1959; Burkert 1977; Sassi 1978: 108-109; Barnes 1982; and Rudolph 2011 all ascribe some role to the effluence from the eye, while Bicknell 1968, Baldes 1975, and Taylor 1999 reject the idea. The evidence for the eye's effluence, however, is minimal. Although Theophrastus' above description suggests that both the visible object and the eye compress the air, Theophrastus does not mention it again as part of the mechanism of vision, even in his critiques of Democritus' ideas, nor does it appear in any other *testimonia*. In any case, even if Democritus does grant a role to an effluence from the eye, which is certainly a possibility, we should not conflate this with the idea that he is proposing a ray-theory alongside his imprint-theory, as Rudolph 2011 suggests. Stating that effluences are emitted from all

Along with the inherent problems of such a theory, there are several difficulties in reconstructing exactly what Democritus is proposing. Some of these difficulties are internal and some are external, but the most substantial hinges on the fact that while Theophrastus makes Democritus' theory entirely dependent on the air as a *medium* for vision, Aristotle suggests that Democritus considered the air something that would *impede* clear sight:

> οὐ γὰρ καλῶς τοῦτο λέγει Δημόκριτος οἰόμενος, εἰ γένοιτο κενὸν τὸ μεταξύ, ὁρᾶσθαι ἂν ἀκριβῶς καὶ εἰ μύρμηξ ἐν τῷ οὐρανῷ
>
> Democritus is wrong in thinking that if the interposed space were empty, one would see accurately, even if there should be an ant in the heavens (Arist. *De an.* 419a16-18).

Many attempts have been made to smooth over this difficulty,[328] but considering what he says about εἴδωλα elsewhere, the most likely answer is either that 1) Aristotle is misinterpreting a doctrine of Democritus' that actually refers to dreams, or 2) Democritus said slightly inconsistent things in different texts. Although I will certainly attempt to

---

things grants no honorific status to the effluence streaming from the eye. Against the earlier attempts of Diels, Beare, and Bicknell to emend the text to κατὰ τοῦ ὁρῶντος, see Burkert 1977: 99, n. 10; cf. Rudolph 2011: 70, n. 16, n. 21.

[327] If Democritus does use the vocabulary of εἴδωλα, it would be unclear whether they would be identified with the effluence leaving the eye, or the 'image' that is transferred *via* the air-imprint into the eye.

[328] Zeller 1920: 1125-28 and Beare 1906: 27 propose that Democritus intended the ant example to be a counterfactual, i.e. because we *cannot* see an ant when the air is gone, we must see *via* an air-imprint. Von Fritz 1953 was the first to emphasize that this discrepancy cannot be so easily overlooked, and he instead proposed that Democritus held two separate theories; cf. von Fritz 1971: 614; see also Bicknell 1968, 1969 and Burkert 1977, who hold similar views. In contrast, Guthrie 1965: 443-444 attempts to solve the problem by arguing that void in the Aristotle passage simply means "void of anything non-transparent," which seems unlikely. Baldes 1975 rejects the proposal that Democritus proposed two theories and instead argues that Theophrastus and Aristotle were talking about two different aspects of vision, insisting that the impression happens in the air *directly in front of the pupil* and that the sun corrals this air. Thus, for Baldes, the celestial ant indicates only that air is required in the immediate vicinity of the eye for vision to occur; cf. Baldes 1976, 1978. Other thinkers, such as Mugler 1959 and Avotins 1980, largely ignore the issue to reinstate a basic version of the εἴδωλα theory, or, as Barnes 1982: 175-176, to adopt the report of Theophrastus over that of Aristotle. Taylor 1999 tries to argue that medium-theory presented by Theophrastus is only describing how vision occurs in the non-ideal scenario of the world, whereas it would *ideally* function as Aristotle describes it were there no air in the way.

address difficulties inherent in Democritus' theory, the primary task of this particular section is not to solve them. Rather, the task at hand is to illustrate that our two competing analogies, the mirror and the wax tablet, are at work within Democritus' account of the eyes.

First, let us deal with the eye as a reflective surface. Although Democritus follows Alcmaeon, Anaxagoras and Diogenes in attributing vision to reflection [ἔμφασις], we should note that Democritus would not explain this reflection in the same way that we do. Like its verbal form ἐμφαίνεσθαι, ἔμφασις literally means "to appear in," and by this Democritus means that the image does not simply bounce off the surface of a reflective surface; it is *implanted* there. Aëtius reports that Leucippus, Democritus and Epicurus all attribute reflection to the fact that εἴδωλα stream from visible objects and form *sediments* [ἐνστάσεις] on the surface of the mirror, which are then "turned back" to the eye [ἀντιπεριστροφήν].[329] Although given Aëtius' questionable conflation of the Atomists and the Epicureans we might hesitate to ascribe this precise theory to Democritus, it is nevertheless quite certain that if Democritus did explain mirrors, he did not attribute reflection to the ricochet of rays, but conceptualized it as effluences collecting *on* the mirror to form an image. We see the image implanted there by means of a second effluence sent back from the mirror's surface.[330]

[329] Aët. 4.14.2 = DK 67 A 31. Plut. *Epit.* 4.14.15 has the term ὑποστάσεις, but Diels, *Dox. Gr.* follows Meineke in the emendation to ἐνστάσεις. Aëtius is clearly referring to the special case where one sees oneself in a mirror, since the εἴδωλα proceed from the viewer to the mirror and then from the mirror back to the eye; cf. Lucr. *DRN* 4. 98-109 for a similar atomist account.

[330] Commentators take Aristotle to understand mirrors in this same way; see Alex. Aphr. *In de sensu* 25.18-26; cf. Prisc. *In Theoph. de sens.* 15-16. Similarly, when Empedocles explains reflections, he describes them as the combination of effluences "made complete" when the fiery part of the mirror separates off from it and mixes with the surrounding air; cf. Aët. 4.14.1 = DK 31 A 88.

Despite having a different conception of how reflection works and interpreting ἔμφασις more literally as an immanent appearance, we should not presume that Democritus is employing the mirror heuristic any less.[331] The term ἔμφασις was a standard word for reflection. For example, Plato mentions how the reflections of letters can "appear in" [ἐμφαίνοιντο] both water and mirrors,[332] and in the *Alcibiades* passage discussed above, the puppet image "appears in" [ἐμφαίνεται] the eye, "just as in a mirror" [ὥσπερ ἐν κατόπτρῳ].[333] Even when Aristotle tries to distinguish between ἔμφασις as an immanent process that occurs in the eye and ἀνάκλασις as a passive affection,[334] Alexander of Aphrodisias clarifies that ἀνάκλασις is another word for ἔμφασις.[335] Thus, although the two terms may implicitly draw on two separate models of reflection, both are nevertheless describing the process that takes place on the surface of mirrors.[336]

In this regard, the mirror seems to influence Democritus' explanation in a way very similar to Anaxagoras'. For instance, in the passage of Theophrastus quoted above, Democritus claims that the air-imprint appears in the eye by virtue of being of a different

[331] *Contra* Rudolph 2011: 77-78.

[332] Pl. *Rep.* 402b4-6.

[333] Pl. *Alcib. I* 132e7-133a5.

[334] Arist. *Sens.* 438a5-9.

[335] Alex. Aphr. *In de sens.* 25.18-20.

[336] Arist. *Sens.* 438a9-10 seems to indicate that the he takes the words as roughly synonymous when he follows his criticism of Democritus by saying "But in general nothing was yet clear concerning reflections and reflection" [ἀλλὰ καθόλου περὶ τῶν ἐμφαινομένων καὶ ἀνακλάσεως οὐδέν πω δῆλον ἦν]. Moreover, although there is some distinction between his use of the two terms, he frequently uses ἔμφασις to describe the images in mirrors: *Mete.* 345a13-26, 373b19-33, 374a16-21, 377b14-18; cf. [Arist.] *De mundo* 395a29-395b1, Arist. *De div. somn.* 464b10-15. Theophr. *De sens.* 36 also seems to view them as synonyms and uses ἀνάκλασις to explain why Anaxagoras argues that only different-coloured objects appear [ἐμφαίνεσθαι] in reflective surfaces.

colour [ἀλλόχρων] from the eye itself.[337] As we saw with Anaxagoras, the idea that only contrasting imprints can appear reflected in the surface of the eye is a conclusion at least supported by, if not actually drawn from, the behaviour of reflective surfaces of the time. Yet, Democritus provides a second stipulation, asserting that the effluence can reflect and appear in the eye precisely because the air-imprint is "solid" [στερεόν]. This is a strange requirement for air. We can understand this idea, however, by realizing that although Democritus has explained the eyes with reference to mirrors, he uses another heuristic to understand reflection. In fact, his insistence that the air-imprints are solid seems to draw directly from the conceptual framework of wax tablets.

The wax tablet was one of the sole indexical technologies in antiquity.[338] Without cameras or printing presses, when ancient theorists attempted to conceptualize and explain how images were transferred and preserved, they most often used an analogy with impressions made in wax. Although footprints in mud would have sufficed just as well, mud is not an image-technology.[339] Instead, as we have seen, theorists tend to use their actual tools as conceptual tools. The philosophical tradition provides many examples of utilizing wax imprints in this way, but the *locus classicus* is found in Plato' *Theaetetus*, where Socrates considers whether the process of memory functions like a "wax mould" [κήρινον ἐκμαγεῖον]. According to this model, when we want to remember objects, we imprint them [ἀποτυποῦσθαι] into the 'wax' of the soul, "just as we impress the marks of signet rings" [ὥσπερ δακτυλίων σημεῖα

[337] Cf. Theophr. *De sens.* 54, where Theophrastus criticizes Democritus for just such an idea.

[338] Other indexical technologies include plaster mould masks, which show up in Lucretius' explanation of vision at *DRN* 4.292-301.

[339] Aesch. *Lib.* 205-211 provides the prototypical example of using footprints as an index for the person who produced them.

ἐνσημαινομένους].[340] Plato was neither the first to use the comparison,[341] nor the last, and the wax tablet analogy survived in many ancient discussions of perception and memory, notably in Aristotle[342] and the Stoics.[343]

I have already partially addressed the influence that the wax tablet had on Democritus, insofar as the air between the eye and its object is "impressed" [τυποῦσθαι], and "imprinted" [ἐναποτυποῦσθαι], while the language of "imprints" [ἀποτύπωσις] and "impressions" [τύπωσις, τύπος] fill his account. Theophrastus makes the analogy explicit:

> πρῶτον μὲν οὖν ἄτοπος ἡ ἀποτύπωσις ἡ ἐν τῷ ἀέρι. δεῖ γὰρ ἔχειν πυκνότητα καὶ μὴ θρύπτεσθαι τὸ τυπούμενον, ὥσπερ καὶ αὐτὸς λέγει παραβάλλων τοιαύτην εἶναι τὴν ἐντύπωσιν, οἷον εἰ ἐκμάξειας εἰς κηρόν.
>
> First, an imprint in the air is illogical. For the thing being imprinted must have density and not crumble, just as he himself says in a comparison, namely that the imprint is just like if you should press a mould into wax (Theophr. *De sens.* 51).[344]

Theophrastus is clear on this analogic scheme, even repeating it in his critiques:

> εἰ δὲ δὴ τοῦτο συμβαίνει καὶ ὁ ἀὴρ ἀπομάττεται καθάπερ κηρὸς ὠθούμενος καὶ πυκνούμενος, πῶς καὶ ποία τις ἡ ἔμφασις γίνεται;
>
> But if this happens, and the air is moulded just like wax, being driven and made denser, how is an immanent appearance [in the eye] formed and what sort of thing is it? (Theophr. *De sens.* 52).

---

[340] Pl. *Tht.* 191c8-e1; cf. 194c4-195a9. At *Phil.* 38e12-c6, Socrates does not use an indexical technology to conceptualize memory, but writing and painting.

[341] Gorg. DK 82 B 11.13, 15 speaks of sight imprinting on the soul.

[342] Arist. *De an.* 424a17-25; 425b23-24; 434a29-30; cf. *Mem.* 450a26-450b1.

[343] For instance, *SVF* I, 55, 58, 59, 64, 66. Burkert 1977: 98, n. 6 provides some modern uses of this analogy as well.

[344] Although Theophrastus uses the terminology ἀποτύπωσις, Democritus seems to have used the term ἐντύπωσις.

This passage alludes to another feature of vision that has not yet been mentioned: light. Democritus attempts to adopt sunlight into his technological heuristic by arguing that light prepares the air for the imprint. It does so by condensing the air, which, as a thin substance, is not particularly conducive to receiving an image on its own. Rather, as the above passage suggests, it needs to be made denser by "being driven together":

> ἀλλ᾽ ἴσως τὴν ἔμφασιν ὁ ἥλιος ποιεῖ <καὶ> τὸ φῶς ὥσπερ ἐπιφέρων ἐπὶ τὴν ὄψιν, καθάπερ ἔοικε βούλεσθαι λέγειν. ἐπεὶ τό γε τὸν ἥλιον ἀπωθοῦντα ἀφ᾽ἑαυτοῦ καὶ ἀποπληττόμενον πυκνοῦν τὸν ἀέρα, καθάπερ φησίν, ἄτοπον.
>
> But perhaps the sun causes the imprint as though carrying light to the eye, just as he seems to want to say. Since it is strange that 'the sun condenses the air, driving it away from itself and pushing it away,'[345] as he says (Theophr. *De sens.* 54).

The light atoms streaming from the sun are not directly responsible for vision and do not enter the eye. Instead, they drive the air in front of them, making it dense enough to receive an imprint from the effluences. Thus, the sun simply prepares the air instead of causing visual perception itself.[346]

Let us situate this particular argument in the larger frame of Democritus' wax-imprint heuristic. Rather than starting from the behaviour of light and sight and then realizing that wax tablets can illuminate their relationship, Democritus starts with the technological analogy and then re-imagines the behaviour of light to fit within his analogic scheme. The wax heuristic must be prior, since what he states about light atoms compressing the air conflicts with his arguments elsewhere. Theophrastus complains

[345] Rudolph 2011: 75 translates ἀποπληττόμενον as the passive "is moulded," taking it to agree with τὸν ἀέρα, but this would render the καὶ superfluous. I therefore follow Stratton 1917: 113 in reading it as a middle-voiced participle agreeing with τὸν ἥλιον and parallel to ἀπωθοῦντα as a participle within the articular infinitive. The middle would thus simply indicate that that the pushing takes place relative to the sun itself, as the reflexive program ἀφ᾽ ἑαυτοῦ indicates.

[346] Burkert 1977: 99.

about this fact, asserting that the sun cannot possibly condense the air, since it should more naturally divide it.[347] Indeed, Democritus claims that fire atoms—which likely share some characteristics with light—divide and move through things precisely by being small, swift and round.[348] In fact, when Theophrastus later describes the action of Democritus' spherical, sweet atoms, he frequently uses verbs with the prefix δια-, as these round atoms "pour *through*" the body [διαχεῖν], "slip *through*" the other atoms [διαδύνειν] and in the process actually make it *softer* and "*more moist*" [ὑγραίνειν], rather than denser.[349] He even appears to have held that owls can see on moonless nights because the fire and heat in their eyes have the capacity to "divide sharply and piercingly" [σφοδρῶς ὀξὺ καὶ τμητικὸν διαιρεῖν].[350] It is possible to construct *ad hoc* hypotheses to account for why round fire atoms divide air in some instances, while even smaller, light atoms somehow manage to push it together into a more cohesive, unified mass—but this is not the point. In using wax-imprint technology as a heuristic, Democritus privileges the technological comparison, so that both air and light need to act

[347] Theophr. *De sens*. 54.

[348] According to Arist. *Cael.* 303a3-b8, Democritus and Leucippus neglected to make clear the shape of other elements, except fire, which they said is composed of round atoms; cf. Arist. *Gen. corr.* 324b35-326b6; *Metaph.* 1078b19-21, Philopon. *Ad phys*. 228.28-229-2; cf. *In gen. corr.* 12.32-13.2. Theophrastus at *De sens.* 68 makes the same claim that the shape of heat is spherical; cf. Arist. *Cael.* 307a16-307b6, which states: "According to Democritus even the sphere, as though being a sort of angle, cuts, since it moves easily…but it is absurd to assign a shape to fire only in reference to division. For it seems rather to aggregate and to bring together rather than divide…so one ought to have been assigned in regards to both, or rather in respect to aggregation." Rudolph 2011: 76 uses this passage to argue that Democritus believes fire atoms combine and connect, despite the fact that Aristotle is chiding him for *not* doing that. This casts doubt on her argument that the fire produces a denser air by getting in between air atoms. It would perhaps harmonize different aspects of what Democritus says, but it is neither what Aristotle suggests in this passage, nor what Theophrastus indicates; cf. Arist. *De an.* 403b25-404a16; *Gen. corr.* 336a3-14; Burkert 1977: 99.

[349] Theophr. *De sens*. 65.

[350] DK 68 A 157. Burkert 1977: 100 incorrectly conflates the fire exiting the owl's eye with the visual ray; cf. Rudolph 2011: 71, n. 27 who warns against this, since the fire is only characteristic of night-vision; cf. Salem 1996: 133.

in ways that at least conflict with, if they do not directly contradict, what he says elsewhere.

Debates about the air as a visual medium have overshadowed another important aspect of Democritus' theory of vision: his physiology of the eye.[351] Although it has not been noticed, the wax tablet model also, in part, extends to the eye itself. Recognizing this can clear up some textual difficulties, as well as allow us to see the degree to which Democritus relies on this single technological heuristic whenever he thinks about image-transfer. Theophrastus provides a description of his eye:

> καὶ τὸ μὲν πυκνὸν οὐ δέχεσθαι, τὸ δὲ ὑγρὸν διιέναι. διὸ καὶ τοὺς ὑγροὺς τῶν σκληρῶν ὀφθαλμῶν ἀμείνους εἶναι πρὸς τὸ ὁρᾶν, εἰ ὁ μὲν ἔξω χιτὼν ὡς λεπτότατος καὶ πυκνότατος εἴη, τὰ δ' ἐντὸς ὡς μάλιστα σομφὰ καὶ κενὰ πυκνῆς καὶ στιφρᾶς σαρκός, ἔτι δὲ ἰκμάδος παχείας τε καὶ λιπαρᾶς, καὶ αἱ φλέβες <αἱ> κατὰ τοὺς ὀφθαλμοὺς εὐθεῖαι καὶ ἄνικμοι, ὡς ὁμοιοσχημονεῖν τοῖς ἀποτυπουμένοις. τὰ γὰρ ὁμόφυλα μάλιστα ἕκαστον γνωρίζειν.
>
> [Democritus says], moreover, that a dense eye does not receive the image, while a moist one lets it in. For this reason, moist eyes are better at seeing than hard eyes, if the outer cover should be as thin and close-packed as possible, and the inside should be as spongy as possible and empty of dense and resistant flesh,[352] still more of clotted moisture and oil. And the passageways connected to the eyes should be straight and dry, so as 'to be of the same shape' as the things being imprinted; for each thing recognizes best what is the same nature (Theophr. *De sens.* 50).

Scholars have taken the passage to indicate that εἴδωλα enter the eyes and simply pass through on their way to the body.[353] If this were the case, however, Democritus would not be ascribing vision to impact [ἐμπτώσεις]. Instead, we must remember that he argues that the images both strike and "appear in" the eye, and therefore cannot simply move

[351] Burkert 1977: 101, for example, gives a single paragraph to it and offers several emendations to Theophrastus' report without argument.

[352] Diels 1879 emends the text to στιφρᾶς, but the meaning is the same.

[353] For instance, Rudolph 2011: 77 agrees that the image must appear on the surface of the eye, but still speaks of the image 'passing through the ducts of the eye.'

through the eye without being visibly imaged on the surface of the pupil. Moreover, this passage also stipulates that the eye must be moist, not dense, since a dense eye will not "receive" [δέχεσθαι] the imprint. These physiological requirements make more sense if we look to the wax imprint heuristic for clarification.

Democritus holds that the eye must be moist, but not hard or dense [πυκνός]; yet, its outer membrane needs to be as fine and "close packed" [πυκνότατος] as possible. By taking the superlative to mean "as *dense* as possible," Burkert thought that the passage was incomprehensible, and he thus proposed to emend πυκνότατος to στιλπνότατος "as gleaming as possible."[354] No such emendation is necessary if we recognize that Democritus is describing the outer surface of the eye as "close packed," insofar as it must be as close as possible to a perfectly uniform, smooth surface to receive the imprint accurately. In this way, it mimics the air, which itself needed to be made more dense [πυκνούμενος] in order to receive an image. If the surface of the eye were not close-packed and unvarying, the imprint received from the 'solid' [στερεόν] air-imprint would be distorted.[355]

The interior physiology of the eye also participates in the imprint analogy, and the stipulations that Democritus provide are also physical characteristics displayed by wax that is capable of receiving a clean, error free image: the inside must be "spongy,"[356] lack

[354] Burkert 1977: 100, n. 23.

[355] Following Stratton, Baldes 1976: 46 takes πυκνότατος to mean "closely knit" and argues that the outer layer's density is used to filter out "inappropriate" atomic structures, i.e. those of sounds and smells. This, however, conflates Democritus' model with Empedocles'. Nowhere does Democritus argue for such a filter.

[356] We could alternatively take "spongy" [σομφά] to mean that the eyes have many pores and passageways though it, especially since the word generally refers to pumice stone; however, "spongy" also describes cuttlefish bone, which can be imprinted; cf. Arist. *Hist. An.* 424b26; Athen. *Deipnosoph.* 9.30.18. Moreover, Arist. *Mete.* 486b7 groups sponges, wax and flesh as "compressible" [πιεστά] substances.

both dense and resistant flesh and be free of pockets of moisture and oil. We can compare these physical attributes of the eye to what Plato says about wax in the *Theaetetus*, where he suggests that the wax most suitable for receiving imprints should be free from rocks, earth and manure, and be neither too soft, nor too hard [ἢ ὑγρὸν σφόδρα ἢ σκληρόν]. The wax should also be evenly kneaded [μετρίως ὠργασμένος], pure and smooth.[357] According to Plato, anything that takes away from the uniformity and receptivity of the wax interferes with proper image-transfer and retention.

Democritus' description of the eye fits this same scheme. He stipulates that the flesh of the eye must be moist and not dense, while also having both a smooth surface and uniform consistency, presumably since any bits of hard or excessively oily flesh would impede the reception of a clean image. In fact, it is hard to understand why hard and oily flesh would prevent image-transfer, if empty pores provided transit for imprinted-air, since these imprints could run around or through such pockets of resistant flesh *via* these passageways. In comparison, Empedocles certainly felt no need to stipulate that the eye could not contain dense or soft parts, since no such a danger intrinsically threatens a pore-theory. It is simply not part of the heuristic's focus. Thus, based on Democritus' physiology of the eye, it seems more likely that he extended the wax-imprint model to the eye itself.

Later doxographical reports seem to include traces of this wax tablet model of the eyes, and Alexander of Aphrodisias takes issue with Democritus on precisely this point:

Theophr. *De sens.* 54 also remarks that, according to Democritus, the eyes must have moisture *and void*. We should note that emptiness in the eye need not be interpreted as simply providing a passageway for atoms flowing through it, since emptiness is precisely what Democritus uses to explain soft substances; cf. Theophr. *De sens.* 62: "The dense substances are hard, while the loose textured ones are soft" [σκληρὸν μὲν γὰρ εἶναι τὸ πυκνόν, μαλακὸν δὲ τὸ μανόν]. In other words, according to Atomist doctrines, all wax would need to be "spongy" (i.e. full of void) in order to receive an imprint.

[357] Pl. *Tht.* 194c4-195a9; cf. 191c6-e2.

> ὅλως δὲ τί γίνεται τὰ προεισελθόντα; τὸ γὰρ φυλάσσεσθαι αὐτὰ λέγειν καταβυσσούμενα καὶ συντίθεσθαι ἐν τῷ ὀφθαλμῷ λίαν ἐστὶ μυθῶδες. ποῦ γὰρ καταβυσσοῦται ἢ μένει…πῶς δέ, εἰ οὕτως ἐστὶ τὰ εἴδωλα εὐπαθῆ, τῇ ἐμπτώσει τῇ εἰς τὸν ὀφθαλμὸν μένει αὐτῶν τὸ σχῆμα καὶ ἡ ἐξοχὴ καὶ εἰσοχὴ καὶ οὐ συγχεῖται;
>
> But in general what are the things that enter in first? *For it is too much myth-speak to say that things 'being buried' are both preserved and established in the eye*. For where are they 'buried' or where do they remain…? And if the *eidola* are easily affected, how do their shape, protuberance and indentation remain in the eye by impression; how do they not run together? (Alex. Aphr. *Mantissa* 135.18-24, emphasis mine).

While Alexander here treats Democritus here as though he were advocating an εἴδωλα model, which we have seen is more likely a conflation with other Atomist doctrines, his critique of Democritus' "myth-speak" [μυθῶδες] suggests that he is attacking actual Democritean vocabulary when he criticizes the notion that the effluence are "buried" [καταβυσσούσθαι] and "preserved" [φυλάσσεσθαι] in the eye.[358] In fact, the only other instance of the word καταβυσσοῦν comes from a passage where Plutarch appears to be quoting Democritus directly, which strongly implies the vocabulary is genuine.[359] Therefore, when Alexander talks about the "impact" [ἔμπτωσις] of this effluence and how its contour would not remain in the eye, but would "run together" [συγχεῖται], he

[358] Alex. Aphr. *In de sensu*. 24.1.15-26 uses this same vocabulary of "preserving" [φυλάττειν] and "saving" [σῴζειν] the image when discussing Democritus' explanation of the eye as a mirror, although he also treats this aspect more generally as an Aristotelian theory of reflective surfaces. The terminology of preservation, however, is not Aristotelian; cf. Alex. Aphr. *In de sensu* 25.1.11-14; 25.20-25; 26.23-25; *In de meterologica* 141. Lucretius may be playing with Democritus' vocabulary of σῴζειν at *DRN* 4.153 when he says that mirrors neither allow *simulacra* to pass through them, nor for the *simulacra* to be broken since: "so much safety the smoothness remembers to maintain" [*quam meminit levor praestare salutem*].

[359] Plut. *Quaes. Conv.* VIII 10, 2 = DK 68 A 77. The difficulty, however, is that whereas Alexander describes this process for the eyes, Plutarch relates it to the εἴδωλα 'being buried' in the pores of the body during sleep. See Avotins 1980: 429, n. 1 for the argument that the word is authentically Democritean.

seems to be alluding to a wax-imprint model, whereby the eye's surface records the actual topography of the implanted image.[360]

To summarize the process of vision as a whole, Democritus proposes that every object sends off effluences that make an impression in the air, which the sun has prepared by compressing it so as to receive an image. As the air-imprint approaches the viewer, it shrinks down under the combined pressure of the effluences behind it and the pressure in front of it (this is generated either by effluences from the eye or simply the surface of the pupil). The air-imprint strikes the eye, where it creates another imprint, an "immanent appearance," that can be seen on the surface of the pupil. This image then moves through the eye and exits through the back, either by moving through the 'wax' ahead of it, or, more likely, by moving through the eye as an imprint in the same way the original impression moved through the air. Unfortunately, because of textual corruption, it is difficult to discern what Democritus imagined taking place as the imprint in the eye exits into the 'veins' that convey the image to the rest of the body.[361]

---

[360] Cf. Alex. Aphr. *Mantissa* 134. 9-10.

[361] Cf. Theophr. *De Sens.* 54. The passage at *De sens.* 50 quoted above merely says that the veins along the eyes must be straight and dry "so as to be the same shape as the things beings imprinted" [ὡς ὁμοσχημονεῖν τοῖς ἀποπυτουμένοις]. The meaning of this phrase, however, is contested. The codices all have "the veins must be straight and dry and *not* well-shaped to the things being imprinted" [καὶ μὴ εὐσχημονεῖν τοῖς ἀποτυπουμένοις], but Diels 1879 emends it to "so as to be well-shaped to the things being imprinted" [ὡς ὁμοισχημονεῖν τοῖς ἀποτυπουμένοις] (although his text was reproduced as ὁμοσχημονεῖν in *Fragmente der Vorsokratiker* II 115, 2, which Stratton 1917 follows; Burkert 1977: 101, n. 24 notices this discrepancy). Diels' emendation is certainly possible, though we may consider whether dropping the μή would produce a more coherent picture, whereby the veins are dry and "easily shaped" by the things being imprinted [καὶ εὐσχημονεῖν τοῖς ἀποπυπουμένοις]. This is supported by the fact that the images in the eye are still called τοῖς ἀποτυπουμένοις, and using the present participle suggests that they are still *being imprinted.* If Theophrastus were merely describing the external air-imprint/effluence, we might expect either the aorist participle or ἀποτυπώσεις. If this is true, it not only supports the idea that the air-imprints themselves make impressions in the eye, it opens up the possibility that yet another instance of image-transfer takes place at the back of the eye as well. If this is the case, image-transfer as a conceptual tool would even have found its way into the conveyance of vision to the soul atoms spread throughout the body. In any case, however, it seems that the things being imprinted on the eye are pushed out of the back of the eye into the veins, which then deliver it to the body as a whole. For sensation taking place throughout the entire body, see Sext. Emp. *Ad math.* VII.349 Taylor 110e.

In general, Democritus displays a version of the same tendency we have been investigating all along: he relies on optical and image-transfer technologies to conceptualize vision and, as a result, attributes certain material features of the technologies around him to the physiology of the eye. Whereas Empedocles and Anaxagoras rely primarily on a single technology to model the eye, Democritus adopts two different technological heuristics to explain vision. Yet, unlike the authors dealt with in the first chapter, he does not apply his explanatory frameworks in alternation as *modal* heuristics, but layers one on top of the other, employing two simultaneous technological analogues, one of which interprets the other. He uses wax tablets to model mirrors to model the processes of vision. In this, he presents an instance of *layered* heuristics and illustrates how deep the impulse can run to reach for technologies as cognitive tools.

3.4 Aristotle, Image-Transfer and the Wax of Memory

Unlike the previous authors, Aristotle is not nearly so beholden to optical technologies for his conceptualization of the mechanisms of vision. His conclusions stem more directly from his overarching philosophical program rather than dependence on technological models. In fact, there seems to be a distinct lack of technological analogues underpinning his conception of both light and sight. That being said, he does incorporate the comparisons used by his predecessors—both the lamp and the wax impression—but to very different ends, and these comparisons do not seem to predicate any physiological features of the eye.[362] By contrast, his conceptual reliance on optical technologies—and

[362] Aristotle incorporates a version of Empedocles' lamp-comparison when providing empirical support for the idea that the eye's operative part is its interior:

> καὶ τοῦτο καὶ ἐπὶ τῶν συμβαινόντων δῆλον· ἤδη γάρ τισι πληγεῖσιν ἐν πολέμῳ παρὰ τὸν κρόταφον οὕτως ὥστ' ἀποτμηθῆναι τοὺς πόρους τοῦ ὄμματος ἔδοξε

image-transfer technologies in particular—seems to be displaced into his account of memory. That is, Aristotle employs a certain philosophical model as a heuristic to explain vision, and thereby constructs the phenomenon in a non image-based way. He therefore does not need to rely on image-transfer technologies for conceptual support. When he discusses memory, however, he begins to think in image-based terms. As a result, he returns to the analogy with wax tablets. This use of the comparison not only affects the way in which he understands the physiology of memory, but also shapes the operations that he imagines take place when we remember something.

> γενέσθαι σκότος ὥσπερ λύχνου ἀποσβεσθέντος, διὰ τὸ οἷον λαμπτῆρά τινα ἀποτμηθῆναι τὸ διαφανές, τὴν καλουμένην κόρην.
> And this is clear in the case of what occurs, for indeed, in war when there are blows against someone's temple in such a way as to cut of the passageways of the eye, darkness seems to fall, just as if a light had been extinguished. This is on account of the fact that the transparent—the so-called 'pupil'—has been cut off, like some lamp (Arist. *De an.* 438b11-16).

Aristotle is arguing that since sight is lost if the optic nerve behind the eye is severed, the eye's watery interior must be the operative part. How this demonstrates Aristotle's point is unclear, since it all that it truly shows is that the eye is the organ with which we see. Nevertheless, we might note that Aristotle has incorporated Empedocles' key analogy, the lamp, into his own explanation of the eye, now somehow shining, as it were *into* the body, not outwards. Unlike Empedocles, however, Aristotle does not use this comparison to construct any anatomical features of the eye. That is, Aristotle considers the eyes to be composed of water, not fire.

In addition, when discussing how the sense organs receive a sense-perception, like Democritus, Aristotle incorporates a comparison to wax impressions:

> καθόλου δὲ περὶ πάσης αἰσθήσεως δεῖ λαβεῖν ὅτι ἡ μὲν αἴσθησίς ἐστι τὸ δεκτικὸν τῶν αἰσθητῶν εἰδῶν ἄνευ τῆς ὕλης, οἷον ὁ κηρὸς τοῦ δακτυλίου ἄνευ τοῦ σιδήρου καὶ τοῦ χρυσοῦ δέχεται τὸ σημεῖον, λαμβάνει δὲ τὸ χρυσοῦν ἢ τὸ χαλκοῦν σημεῖον, ἀλλ' οὐχ ᾗ χρυσὸς ἢ χαλκός· ὁμοίως δὲ καὶ ἡ αἴσθησις ἑκάστου ὑπὸ τοῦ ἔχοντος χρῶμα ἢ χυμὸν ἢ ψόφον πάσχει, ἀλλ' οὐχ ᾗ ἕκαστον ἐκείνων λέγεται, ἀλλ' ᾗ τοιονδί, καὶ κατὰ τὸν λόγον.
> In general, it is necessary to understand that with regard to every faculty of sensation that sensation is that which is receptive of the sensible forms without the matter, just as wax receives the mark of the ring although without the iron or gold, and it receives the golden or brazen mark, but not *as* gold or *as* bronze. Similarly, the faculty of perception too is affected by each thing that has colour, or flavour, or sound, but not by virtue of which each of these things is said to be, but by virtue of the fact that it is a certain type of thing, and according to its ratio (Arist. *De an.* 424a17-21).

There is much debate over this passage, especially as to whether "receiving the sensible forms without the matter" indicates that the sense organ receives the perceptible qualities without any material *substance* being transferred, or whether "without the matter" is indicating that no material is involved at all, and instead what is involved is a simple awareness of the colour reaching it; cf. n. 373 below for this debate. Either position has similar consequences for my overall argument, namely, that this comparison, used to illustrate how all the senses can perceive objects, does not change Aristotle's physiology of the eye, nor of any of the other organs of sense. Aristotle's eye is made out of neither wax nor fire.

Aristotle's account of vision is far more philosophically sophisticated than those we have seen in Empedocles, Anaxagoras and Democritus. Indeed, he articulates a larger metaphysical structure underlying the five faculties and establishes that each sense has its own proper object that only it can perceive; these he calls the "proper sensibles" [ἴδια αἰσθητά].[363] Aristotle defines vision's proper sensible as the "visible" [τὸ ὁρατόν], which he then further specifies as colour (as well as the related phenomenon of luminescence).[364] That is, Aristotle argues that when we look at the world, what we see in the most basic sense is colour, and it is only by virtue of it that we are able to see other visual characteristics.[365] In turn, he defines colour as that which is productive of change [κινητικόν] in the visual medium. He notes that the most common visual medium is air, although he points out that multiple material substances can fill this role, including water

[363] Arist. *De an.* 417b10. For instance, taste's proper sensible must be flavour, since we cannot hear, see, smell or touch flavour; it is the province solely of taste. Similarly, smell's proper sensible is odour, while hearing's is sound. Touch, for its part, breaks the mold slightly, insofar as it maintains several proper sensibles, including heat/cold, dry/wet and rough/smooth. As this last example suggests, Aristotle argues that all sensible qualities operate according to a set of fundamental oppositions (e.g. bitter/sweet for taste, or high/low for sound), and all sensations exist on the continuum between these such poles (*De an.* 422b24-34). Although the senses generally operate according to a single set of oppositions, they can occasionally perceive multiple sets, such as how hearing perceives high/low pitch as well as loud/soft; cf. *Sens.* 442b18-21, 445b24-26. Those qualities that are perceived by more than one sense faculty he calls the "common sensibles" [κοινὰ αἰσθητά]. These include motion, rest, number, shape and size [κίνησις, ἠρεμία, ἀριθμός, σχῆμα, μέγεθος] (*De an.* 422b17-34).

[364] What Aristotle actually says, is: "The object of sight is the visible, and this is either colour, or something which can be described in words, but has no name [οὗ μὲν οὖν ἐστιν ἡ ὄψις, τοῦτ' ἐστὶν ὁρατόν, ὁρατὸν δ' ἐστὶ χρῶμά τε καὶ ὃ λόγῳ μὲν ἔστιν εἰπεῖν, ἀνώνυμον δὲ τυγχάνει ὄν] (Arist. *De an.* 418a26-28). At *De an.* 419a4-5, he clarifies that he is referring to "fiery things" [τὰ πυρώδη] and "gleaming things" [λάμποντα] such as fungi and fish eyes; cf. *Sens*. 437b6-7. Aristotle is not the first to make colours the prime sense object of vision; cf. Pl. *Tim*. 67c4-7; *Rep.* 507d11-e5.

[365] For example, when we see a red ball, we perceive it by virtue of its redness, not by virtue of its roundness. The latter we perceive only as a derivative, incidentally visual quality, since even without seeing the ball, you can tell that it is round by touching it, but you cannot tell that it is red. We neither see people *qua* people, nor chairs *qua* chairs, since neither of these things have visibility as part of their essential nature: they can still *be* people and chairs even in a totally dark room; they are visible only accidentally [κατὰ συμβεβηκός] (Arist. *De an.* 418a21-23). Aristotle provides the example of seeing a white thing that is the son of Diares. Being white is what makes him visible, while being the son of Diares is incidental to this perception. In contrast, we do not see red accidentally, but by virtue of what it is.

and, as he says, "many solid substances."[366] Accordingly, Aristotle does not hold the visual medium to be any particular material, but a capacity common to multiple substances—a capacity that he calls the 'transparent' [τὸ διαφανές].[367] He is careful to clarify that colour cannot cause vision alone, since it is not visible in and of itself [καθ᾽αὑτό]. Instead, it requires light to be made actually visible. Light, in turn, he defines as the *presence* [παρουσία] of fire—or at least something like fire—in the air, which actualizes the transparent as a visual medium. To use his precise formulation, "light is the actuality [of the transparent], *qua* transparent" [φῶς δέ ἐστιν ἡ τούτου ἐνέργεια, τοῦ διαφανοῦς ᾗ διαφανές].[368] Vision occurs insofar as colour produces some form of qualitative alteration across this active transparent visual medium, instantaneously reaching the eye.[369] As Aristotle states: "colour produces change in the transparent, such as the air, and the sense organ is changed by this insofar as the air is continuous" [τὸ μὲν χρῶμα κινεῖ τὸ διαφανές, οἷον τὸν ἀέρα, ὑπὸ τούτου δὲ

---

366 Arist. *De an.* 418b6-7. Although we many think straightway of glass, Aristotle does not actually mention this material in his discussion of vision.

367 To put this another way, we see by means of the air, but not *qua* air, only *qua* transparent, which is the vehicle by which colours reach us. In fact, Aristotle claims that without this medium (e.g. if we were to place an object directly on our eye) we would not see at all; cf. Arist. *De an*. 423b17-23. In other words, he considers the transparent medium to be a necessary condition of visual perception. Arist. *De an*. 419a26-b4 extends this idea as a general principle for all the senses, claiming that all sense perceptions require a medium. Hearing and smell fit this paradigm relatively well, since both pass through the air; taste and touch, however, present more of a problem; cf. Arist. *De an*. 422a8-19, 423a22-b26. Lloyd 1996: 126-137 examines to what degree Aristotle's model of perception can be generalized, i.e. whether complete parallelism exists across all five senses and whether this model can be extended to all animals (most notably the bloodless animals). He rightly concludes that while Aristotle may want to produce a universally applicable account, his empirical observations occasionally produce difficulties.

368 Arist. *De an.* 418b9-10. In other words, light is simply the activity of the transparent being transparent and clear. In some ways, this is quite obvious. Without the presence of a fire-like substance, air is dark (and thus not transparent in actuality). Darkness is therefore simply the removal of the transparent's active condition. In other words, light and darkness are the active and potential states of the same underlying substance, or, as Arist. *De an*. 418b31-419a1 states: "The same nature is sometimes dark, and sometimes light" [ἡ γὰρ αὐτὴ φύσις ὁτὲ μὲν σκότος ὁτὲ δὲ φῶς ἐστιν].

369 Cf. Arist. *Sens*. 438b2-5.

συνεχοῦς ὄντος κινεῖται τὸ αἰσθητήριον].[370] That is, colour alters the transparent, and the alteration in the transparent alters the eye in turn.

Having articulated how colour gets *to* the eye, so to speak, it still remains to discuss how colour is seen *by* the eye. In many ways, Aristotle simply extends the model he has already developed for the transparent medium:

> εἴτε φῶς εἴτ' ἀήρ ἐστι τὸ μεταξὺ τοῦ ὁρωμένου καὶ τοῦ ὄμματος, ἡ διὰ τούτου κίνησίς ἐστιν ἡ ποιοῦσα τὸ ὁρᾶν. καὶ εὐλόγως τὸ ἐντός ἐστιν ὕδατος· διαφανὲς γὰρ τὸ ὕδωρ, ὁρᾶται δὲ ὥσπερ καὶ ἔξω οὐκ ἄνευ φωτός, οὕτως καὶ ἐντός· διαφανὲς ἄρα δεῖ εἶναι· ἀνάγκη ἄρα ὕδωρ εἶναι, ἐπειδὴ οὐκ ἀήρ. οὐ γὰρ ἐπὶ ἐσχάτου τοῦ ὄμματος ἡ ψυχὴ ἢ τῆς ψυχῆς τὸ αἰσθητικόν ἐστιν, ἀλλὰ δῆλον ὅτι ἐντός· διόπερ ἀνάγκη διαφανὲς εἶναι καὶ δεκτικὸν φωτὸς τὸ ἐντὸς τοῦ ὄμματος.
>
> Whether the medium between the visible object and the eye is light or air, change through this [medium] causes seeing. And it is reasonable that the interior is composed of water; for water is transparent. And just as vision does not take place outside without light, so too on the interior. Therefore, it is necessary that there is a transparency. Therefore, this must be water, since it is not air. For the soul or the sensory part of the soul does not reside at the surface of the eye, but it is clear that it is on the interior; for this very reason, the interior of the eye must be transparent and receptive of light (Arist. *Sens.* 438b3-11).

Aristotle's argument here is that light is required to transmit colour outside of the eye, and so must therefore be part of the mechanism of vision on the inside of the eye as well. Since light is the actualization of the transparent, the eye must thus be transparent.[371] The eye therefore functions not through any mirror-like quality of its surface, but because of

[370] Arist. *De an*. 419a13-14.

[371] Arist. *Sens*. 438a14-20 asserts that since both air and water are transparent, the operative material of the eye must be constituted out of one of these two substances. Since air is harder to contain, it must be water, and indeed, when eyes decay, they ooze liquid. This particular argument led Nussbaum and Putnam 1992 to attribute a functionalist position to Aristotle, whereby he proposes only certain parameters that must be met for the sense organs to operate, but holds that multiple materials compositions could meet those requirements.

the transparent water in its interior, which is capable of "receiving light" [δεκτικὸν φωτὸς] just as the outside transparent air.[372]

What type of alteration actually occurs when the transparent eye "receives" colour has been a topic of considerable debate, dominating almost all recent discussions of Aristotle's theory of perception. For my present purposes, it only matters that Aristotle constructs vision as an act whereby the eye adopts a single colour, whether this takes place literally or psychically.[373] That is, Aristotle constructs a heuristic to explain how the eye sees a red ball by 'becoming' red, but does not explain how the eye sees an image of a house by becoming all the colours of the house. As was stated at the beginning of this chapter, by applying a heuristic to a problem, theorists become 'selectively myopic' in order to construct a target fieldof explanation in a particular way. In explaining vision as he does, Aristotle not only constructs it as a phenomenon with one proper sensible, colour, but also implicitly as a process whereby a single organ adopts a single colour at a single moment in time.

This construction of vision's essential nature helps us understand the somewhat curious discussions at *Sens.* 447a13-15, where Aristotle asks whether it is possible to

---

[372] Cf. Arist. *De an.* 418b26-29, where Aristotle states that it is the colourless that is receptive of colour.

[373] The debate surrounds the interpretation of a key passage, which indicates that the eye, just as every sense organ, takes on some relevant quality of its object, thereby "becoming like" the object it perceives:

> τὸ δ᾽ αἰσθητικὸν δυνάμει ἐστὶν οἷον τὸ αἰσθητὸν ἤδη ἐντελεχείᾳ, καθάπερ εἴρηται. πάσχει μὲν οὖν οὐχ ὅμοιον ὄν, πεπονθὸς δ᾽ ὡμοίωται καὶ ἔστιν οἷον ἐκεῖνο.
> The sense organ is potentially such as the sensible object is already in actuality, just as was said. Thus, since [the sense organ] is not like [its object], it is affected, and having been affected, it becomes like and is such as that sensible object (Arist. *De an.* 418a3-6).

It is unclear precisely what Aristotle means when the eye "becomes like" its sense object, whether he intends that the interior transparency of the eye literally takes on the colour of its object (cf. Sorabji 1972a, 1972b, 1974, 1992; Slakey 1961), whether he is instead suggesting that only a non-physical alteration takes place, equivalent to the visual faculty simply "becoming aware" of its object (cf. Burnyeat 1992, 1993, 2001, 2002; Broadie 1993; Murphy 2005; Lorenz 2007), or whether he is proposing a hylomorphic position equivalent to some hybrid of the two (Everson 1997; Johansen 1997; Charles 2011; cf. Nussbaum 1978 and Nussbaum and Rorty 1992, who put forth a related, functionalist position).

perceive two things in the same part at the same indivisible time [ἐν τῷ αὐτῷ καὶ ἀτόμῳ χρόνῳ]. He wonders whether the stronger of the two sensations will always override the weaker.[374] The example that Aristotle provides occurs across multiple senses, such as when we fail to hear someone speaking because we are lost in thought, but he also brings up a more general observation, namely that it is easier to taste pure wine than mixed, hear a single note rather than a chord and see a pure colour rather than a mixed one.[375] In other words, as part of this general line of questioning, he asks whether we can perceive two different sensory qualities, such as sweet and sour, or red and blue, with the same organ simultaneously. If we can, this presents a problem, since, on the one hand, if we perceive opposing qualities such as high and low, or white and black separately, we will have to conclude that there are multiple operative parts with the sense organ and the sense organs themselves will thus each be multiple;[376] on the other hand, if a single, unified part perceives all these opposing qualities simultaneously, it will need to *adopt* multiple opposing qualities at the same time. How do these opposites not simply cancel each other out?[377]

Ultimately, Aristotle suggests that there must be some relevant part of the soul that can perceive different and opposing qualities simultaneously. Regardless of his solution, however, the fact that Aristotle is concerned with these questions in the first place demonstrates that he is conceptualizing vision as the interaction between individual, colours and a single transparent eye. Aristotle is not thinking about vision in terms of

[374] See Burnyeat 1993 for a discussion of this aspect of Aristotle's theory.

[375] Arist. *Sens.* 447a18-20.

[376] Arist. *Sens.* 447b10-16; 448b30-449a1.

[377] Arist. *Sens*. 448a2-6.

images, pictures, or what we might now consider 'screen shots.' His model operates with individual colours affecting the eye *via* the transparent visual medium.[378] What happens when Aristotle needs to think in terms of images? What happens when he needs to conceptualize how memory preserves faces or objects, for instance, and not simply 'red'? It is at this point that the wax tablet heuristic re-enters his account.

Aristotle presents his most thorough account of memory in *De memoria*, which explicitly follows *De sensu et sensibilibus*.[379] He describes it as follows:

> ἔστι μὲν οὖν ἡ μνήμη οὔτε αἴσθησις οὔτε ὑπόληψις, ἀλλὰ τούτων τινὸς ἕξις ἢ πάθος, ὅταν γένηται χρόνος. τοῦ δὲ νῦν ἐν τῷ νῦν οὐκ ἔστι μνήμη, καθάπερ εἴρηται [καὶ πρότερον], ἀλλὰ τοῦ μὲν παρόντος αἴσθησις, τοῦ δὲ μέλλοντος ἐλπίς, τοῦ δὲ γενομένου μνήμη· διὸ μετὰ χρόνου πᾶσα μνήμη.
>
> On the one hand, memory is neither sensation nor judgment, but is a state or affection of one of these whenever time has passed. On the other hand, there cannot be memory of the present moment in the present moment, just as has been said, but perception is of the present, expectation of the future and memory of what has happened; for this reason all memory occurs with [the passing of] time (Arist. *Mem.* 449b24-28).

It may seem obvious that memory can involve only things that have already happened in the past, but Aristotle moves on to assert something far more contentious, namely that all memory requires *mental images* [φαντάσματα] and belongs to that same part of the soul to which mental imaging [φαντασία] belongs:[380]

[378] Cf. Arist. *De an.* 418a21-23. See also, n. 373 above. This is not to insist that Aristotle could *not* adjust his heuristic so as to accommodate images and other aspects, merely that in constructing vision as he does, the operative model functions with a single colour being received, not an image.

[379] Arist. *Sens.* 449b1-3.

[380] As with most technical terms in Aristotle, it has proven quite difficult to determine precisely what Aristotle means by φαντασία. Traditional readings interpreted this word as 'imagination,' which brought along aspects such as projection and fantasy. In contrast, Nussbaum 1978: 248 has argued that imagination has propositional content and therefore should be considered the faculty of interpreting sense perceptions, by which we turn disparate sense data (e.g. red, round) into a propositional statement (e.g. this is a ball); cf. Wedin 1988; Caston 1996, 1998; and Labarrière 1984, 2004 for approaches along these lines. Others have shown the contradiction in Nussbaum's account, such as Everson 1997: 164, n. 5. In contrast, King 2006

τίνος μὲν οὖν τῶν τῆς ψυχῆς ἐστι μνήμη, φανερόν, ὅτι οὗπερ καὶ ἡ φαντασία· καί ἐστι μνημονευτὰ καθ' αὑτὰ μὲν ὧν ἐστι φαντασία, κατὰ συμβεβηκὸς δὲ ὅσα μὴ ἄνευ φαντασίας.

It is clear, then, that memory belongs to a certain part of the soul to which mental imaging also belongs. And all objects of memory are also objects of mental imaging in and of themselves, while all the things that cannot exist without mental imaging are objects of memory only incidentally (Arist. *Mem.* 450a22-25).

Aristotle declares that memory must require a φάντασμα because, as he also argues, thinking requires one as well. As an example, he suggests that when we think of abstract entities, such as a triangle, even though they do not have finite magnitude, we still "place (a triangle of) a certain size before ours eyes" [τίθεται πρὸ ὀμμάτων ποσόν].[381] That is, we cannot think about the relationships between a triangle's three sides without placing an image of some particular triangle in front of our mind's eye.

This emphasis on visuality is key to understanding the nature of Aristotle's physiology of memory, since it allows us to see a shift in the way he characterizes and conceptualizes the retention of 'things that have happened' by resorting to image-based concepts. As a result, when Aristotle seeks to explain the mechanisms of memory, he incorporates a comparison to the two paradigmatic image technologies, the painting and the wax tablet:

ἀπορήσειε δ' ἄν τις πῶς ποτε τοῦ μὲν πάθους παρόντος τοῦ δὲ πράγματος ἀπόντος μνημονεύεται τὸ μὴ παρόν. δῆλον γὰρ ὅτι δεῖ νοῆσαι τοιοῦτον τὸ γιγνόμενον διὰ τῆς αἰσθήσεως ἐν τῇ ψυχῇ καὶ

downplays the imagistic content of φαντασία and argues that it means 'representation,' but this is to place too little emphasis on the visual requirement of the term. In this regard, Schofield 2011: 124 acknowledges that φαντασία seems to have propositional content, but he stresses it visual component; cf. Calvo-Martínez 2011. I follow this latter approach, since the word has strong visual connotations, as the etymological root of 'appearance' [φαν-] implies. Moreover, while Aristotle may use the term to encompass more than a purely visual conception of mental images (for instance, one including smells, sounds, etc.), it is still clear that Aristotle is using visual images as his basic root concept and adapting this core meaning to other contexts.

[381] Arist. *Mem.* 449b30-450a13; cf. *De an.* 431a14-17; 431b2-432a13; see also Sorabji 1972a: 8.

τῷ μορίῳ τοῦ σώματος τῷ ἔχοντι αὐτήν—οἷον ζωγράφημά τι [τὸ πάθος] οὗ φαμεν τὴν ἕξιν μνήμην εἶναι· ἡ γὰρ γιγνομένη κίνησις ἐνσημαίνεται οἷον τύπον τινὰ τοῦ αἰσθήματος, καθάπερ οἱ σφραγιζόμενοι τοῖς δακτυλίοις.

Someone would be at a loss how at times—although the effect from it is present—we remember the thing itself, even though it is absent. For it is clear that it is necessary to consider such an occurrence through sense-perception in the soul and *in the part of the body that holds on to it*, as though the effect were a painting, the lasting state of which we call memory. *For the change that arises makes an imprint of the thing perceived like some stamp, just as some men seal things with signet rings* (Arist. *Mem.* 450a26-450b1, emphasis mine).

The comparison to wax signet rings may at first appear entirely metaphorical,[382] but the physiology that Aristotle describes appears to take this figurative language quite literally. In fact, the passage above continues:

διὸ καὶ τοῖς μὲν ἐν κινήσει πολλῇ διὰ πάθος ἢ δι’ ἡλικίαν οὖσιν οὐ γίγνεται μνήμη, καθάπερ ἂν εἰς ὕδωρ ῥέον ἐμπιπτούσης τῆς κινήσεως καὶ τῆς σφραγῖδος· τοῖς δὲ διὰ τὸ ψήχεσθαι, καθάπερ τὰ παλαιὰ τῶν οἰκοδομημάτων, καὶ διὰ σκληρότητα τοῦ δεχομένου τὸ πάθος οὐκ ἐγγίγνεται ὁ τύπος. διόπερ οἵ τε σφόδρα νέοι καὶ οἱ γέροντες ἀμνήμονές εἰσιν· ῥέουσι γὰρ οἱ μὲν διὰ τὴν αὔξησιν, οἱ δὲ διὰ τὴν φθίσιν. ὁμοίως δὲ καὶ οἱ λίαν ταχεῖς καὶ οἱ λίαν βραδεῖς οὐδέτεροι φαίνονται μνήμονες· οἱ μὲν γάρ εἰσιν ὑγρότεροι τοῦ δέοντος, οἱ δὲ σκληρότεροι· τοῖς μὲν οὖν οὐ μένει τὸ φάντασμα ἐν τῇ ψυχῇ, τῶν δ’ οὐχ ἅπτεται.

For this reason (i.e. that memory occurs in the body because of an impression like that of a signet-ring in wax), memory does not arise in some people (whether because of disability or age) even with a great impetus, as though the impetus and signet ring were falling against flowing water. But for others (memory does not occur) because it is scratched away, just like old walls in buildings, and the impression does not make any effect because of the hardness of the receiving surface. And for this very reason the excessively young and excessively old both have bad memories; for the former flow because of their growth, while the latter because of their decay. Similarly, those who are too quick or too slow do not appear to have good memories either; for the former are *more moist than is required*, while the latter are too hard; and so for some the

[382] King 2009, esp. 7-11, 2010 proposes a non-physical account of memory, rejecting the idea that there would be, as he puts it, a picture gallery in one’s head, which he considers ridiculous; cf. Mackie 1976: 41-47 for the opposite view.

> image does not remain in the soul, but for other, the image does not even affix itself (Arist. *Mem.* 450a32-b11).

This passage operates right at the pivot point between soul and body, just as affections such as perception and memory do as well. It talks about the image remaining in the soul, all while providing the physical circumstances that allow for such image-retention. Yet, in examining the physiologies that Aristotle is describing, we can see that the analogy with the wax tablet has provided Aristotle with a heuristic through which to interpret the pathologies of the human body. By imagining that memory works as wax does, Aristotle ascribes the effectiveness of one's memory to the moisture levels in one's body, since the level of moisture in wax affects its ability to receive an imprint.[383] These seem to be the same pathologies of memory described by Plato in the *Theaetetus* and discussed in relation to Democritus above. For all his talk about transparency and actualization, when Aristotle actually talks about image-transfer and retention, he relies on the same analogy that Democritus used before him, and this leads him to think about the body through a technological heuristic. In fact, what was originally an analogy and a metaphor, very quickly seems to become literally true as the physiology of memory takes on physical characteristics of actual wax.[384]

[383] Aristotle is not alone in suggesting that our mental faculties rely on our moisture levels. For instance, *Anon. Lond*. 11.22-42 reports that Hippo of Croton considered old people dry, while holding moisture responsible for sensation. Similarly, Theophr. *De sens.* 45 claims that for Diogenes children are foolish because of excessive moisture; cf. Theophr. *Sudore* 19. Excessive moisture appears as a pathology throughout the Hippocratic corpus; cf. [Hippocr.] *Vict.* 2.66; cf. Holmes 2010: 186. This is all to say that the wax tablet model does not predicate physiology, but simply allows Aristotle to reinterpret existing ideas within a new explanatory framework. The wax tablet provides a heuristic in which *both* moisture *and* memory can find meaning.

[384] Arist. *Mem*. 453a31-b4 mentions the physiological conditions responsible for memory, stating that dwarves have bad memories because their big heads place a lot of weight on their perceptive faculty; cf. *Ins*. 462b5-8, which describes certain physiological features that make it difficult for people to dream.

The literalization of this comparison leads to another instance of analogic drift, although not about the physiology of memory, but about the type of activities that memory involves. The wax tablet analogy changes the operational definition of memory as a process. It happens when Aristotle asks how we can remember an object's size, even when we are no longer looking at it. He is confused, since all internal imprints are, by necessity, quite small. His solution is that we must use geometry to calculate their relative sizes (fig. 10):

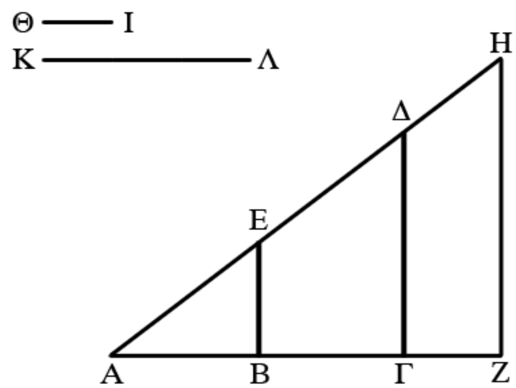

Fig. 10 Aristotle's Geometry of Memory (*Mem.* 452b13-23)

τίνι οὖν διοίσει, ὅταν τὰ μείζω νοῇ, ὅτι ἐκεῖνα νοεῖ ἢ τὰ ἐλάττω; πάντα γὰρ τὰ ἐντὸς ἐλάττω, καὶ ἀνὰ λόγον [καὶ τὰ ἐκτός]. ἔστι δ' ἴσως ὥσπερ καὶ τοῖς εἴδεσιν ἀνάλογον λαβεῖν ἄλλο ἐν αὑτῷ, οὕτως καὶ τοῖς ἀποστήμασιν. ὥσπερ οὖν εἰ τὴν AB BE κινεῖται, ποιεῖ τὴν ΓΔ· ἀνάλογον γὰρ ἡ AΓ καὶ ἡ ΓΔ. τί οὖν μᾶλλον τὴν ΓΔ ἢ τὴν ZH ποιεῖ; ἢ ὡς ἡ AΓ πρὸς τὴν AB ἔχει, οὕτως ἡ Θ πρὸς τὴν I ἔχει; ταύτας οὖν ἅμα κινεῖται. ἂν δὲ τὴν ZH βούληται νοῆσαι, τὴν μὲν BE ὁμοίως νοεῖ, ἀντὶ δὲ τῶν ΘI τὰς KΛ νοεῖ· αὗται γὰρ ἔχουσιν ὡς ZA πρὸς BA.

Whenever one thinks about larger things, how will it differ from thinking about smaller things? For *all internal things are smaller* and proportionate. But perhaps just as is possible to have a ratio with shapes, another in relationship to itself, so too with distances. And so if one is moved with respect to AB and BE, he produces ΓΔ; for AΓ and ΓΔ are in the same ratio. Why then does he produce ΓΔ rather than ZH? Surely because AΓ has the same ratio to AB as Θ to I. Thus, he has these

> impulses simultaneously. But if he wants to imagine ΖΗ, he keeps ΒΕ in mind, but instead of ΘΙ, he thinks of ΚΛ; for these are in the same relation as ΖΑ to ΒΑ (Arist. *Mem.* 452b13-23).

In the above passage, Aristotle is proposing that we can remember both distances and sizes of objects by calculating their relative magnitudes using the similar triangles that mark their distance (AB) and the height (BE). This seems to be a poor solution, question begging to say the least, since if all memories are abstract, disembodied images, how do they have any magnitude in memory? If the images were non-physical, how would they have any size that could be compared? If calculating were meant metaphorically, how would his explanation offer any help? Because of these difficulties, I argue that Aristotle treats these memories as actual physical imprints, which reveals just how literal this wax analogy has functionally become. Even if only to advance this part of his theory, he seems to be conceiving of memories as little static images imprinted upon the wax of the memory part of the soul. Within this model, the mind takes the place of an embodied viewer, manipulating and observing the images in front of him as though he were holding a wax tablet.

What would wax have been used for in fourth century BCE Greece, especially in places like the Academy and the Lyceum? We have seen how it preserves image-impressions from signet rings that can be verified later, but another common use was to spread it across boards so at to write on it. Not only could letters be written on these surfaces, but images from pottery vessels also indicate that students used them for schoolwork. It seems very likely that mathematical problems, especially geometric problems, would have been solved using diagrams on a wax tablet. It may come as no surprise, then, that Aristotle imagines that the soul uses this implement in just this way, as it 'does geometry' with the diagrams imprinted upon the wax block of memory. In fact, he has provided a macro-version of what such a memory-diagram must look like in the tiny recesses of our body.

Is sum, despite his philosophically sophisticated treatment of both vision and memory, when he thinks about image-transfer and retention, he relies on conceptual tools similar to those of his predecessors. Yet, Aristotle not only takes some of the physical attributes of wax and applies them to the physiological explanation of memory, but he also conceptualizes the act of remembering according to some of the *practical* applications of wax as well. Whereas we might think about memory *via* our technologies and implicitly presume that it functions as a type of video recording, Aristotle conceptualizes the act of memory *via* his technologies and presumes that our mind's eye looks upon a proportional imprint left in the wax of our soul. Before we dismiss Aristotle's assumptions as fanciful or unscientific, we should realize that memory in no real way works like video. We cannot press play on old memories. We simply adopt this heuristic from our own technological world, reflexively, automatically, naturally and perhaps without much hesitation.

3.5 Conclusion

In this chapter, I have examined four different accounts of vision, each of which focuses on and privileges different aspects in the process of sight. Empedocles adopts the lamp as a metonym for the eye, letting it guide both his physiological account and his explanation of night-vision despite the fact that this basic technological heuristic conflicts with his general theory of perception. With Anaxagoras, I illustrated how a philosophical position can derive conceptual support from technological implements. In this case, the assumption that reflection *qua* reflection takes place by virtue of contrast is rooted in the use of bronze mirrors in antiquity, even if it aligns with a wider philosophical framework of perception by opposites. In turn, I articulated how Democritus adopts not only a mirror analogy to understand the eye, but also a wax tablet analogy to explain the mirror. In this way, he uses one technological heuristic to comprehend another. Different technologies function more effectively to conceptualize different moments in the process of vision, but unlike the *modal heuristics* of chapter one, Democritus employs his *layered heuristics* almost simultaneously. Lastly, I examined how Aristotle's theory of vision constructs visual perception as an interaction between a single, transparent eye and a single colour. In so doing, he uses no technological heuristic to conceptualize image-transfer. Yet, when he discusses memory and needs to think in terms of image-retention, he returns to the wax tablet heuristic, which structures certain assumptions about the physiology of memory, while also predicating what Aristotle presumes actually takes place when we remember something. The wax tablets in the body thus get used in the same way as wax tablets in the world.

Chapter Four
Optical Diagrams as Physical Heuristics

4.0 Diagrams as Physical Heuristics

In this chapter, I will turn my focus away from material technologies *adopted* as physical heuristics in order to examine a technology that is constructed to explain natural phenoemena more directly. In particular, I am interested in the application of geometrical diagrams to explanations of sight. How does this type of technology affect ideas about the physical process of vision? How do these images shape assumptions about the entities involved in visual perception and the mechanics of the eye? Instead of viewing these geometrical images as the *result* of a technological heuristic, as I did with Aristotle's account of memory, I will examine how they create an active physical heuristic of their own. To this end, I will focus on two main authors, Aristotle and Euclid, and will explore how their geometrical practices and technologies infiltrated physical conceptions of eyesight and became incorporated into ideas about the mechanism of vision. I will show how the technologies used to represent and articulate eyesight shaped both ideas about its physical nature and theorists' experience of it. In this regard, diagrams—while abiding by a unique set of internal rules—fill a role similar to that of technological analogies. In fact, although the analogy may not be as explicit, diagrams too function by a type of comparison, since the whole premise of ancient applied mathematics—geometrical optics included—rests on an implicit assumption: as in the diagram, so too in the world. From this standpoint, I ask what it means to draw a mathematical picture of something in order to explain it, and, perhaps more importantly, what are the consequences of this particular technology for ancient physical theories.

Geometrical optics must have existed in some form by at least the early fourth century BCE century, since Aristotle mentions it as though it were an already established geometrical practice.[385] It was during the Hellenistic period, however, that the practice flourished more broadly, developing into a full branch of mathematics encompassing several subsections, including both catoptrics and dioptrics.[386] During this period, the diagram became one of the most important conceptual tools for the scientific treatment of vision and light—in other words, it became one of the chief optical technologies. It is precisely its status as a conceptual tool that I would like to interrogate. But, before I start talking about the effects that ancient diagrams had on natural inquiry, I ought to outline what these diagrams would have looked like, especially since ancient Greek mathematical practices were somewhat different from our own and did not emerge fully formed.[387] The majority of evidence is handed down in two ways: 1) images preserved in the manuscript tradition; and 2) textual references and their accompanying proofs.[388]

[385] Arist. *Ph.* 194a7-12; *Metaph.* 997b20-21; 1077a4-7; 1078a14-15; *An. post.* 75b14-17; 76a23-25; 77b1-4; 78b36-39; 79a10-21. The Suda IV, 733, 24-34 [Adeler] also lists one of the member of Plato's Academy, Philip of Opus (*fl. c.* 350 BC) as having written both an ὀπτικῶν and an ἐνοπτ(ϱ)ικῶν, along with other works concerning eclipses and the sizes of heavenly bodies; cf. Tarán 1975: 115-139. For his part, however, Plato seems ignorant of mathematical optics, since he neither mentions it, nor incorporates it into the theories of eyesight in the *Timaeus*. Plato does, however, acknowledge related geometrical treatments of celestial illumination, and we might consider whether the analogies of the sun and the divided line (*Rep.* 509d1-517a5) draw from this tradition; cf. n. 325 above.

[386] Texts belonging to the tradition of geometrical optics include: (pseudo-) Euclid's *Catoptrics*, pseudo-Aristotelian *Problemata* (book 15), Archimedes' *Catoptrics*, Diocles' *On Burning Mirrors*, Hero's *Catoptrics*, Ptolemy's *Optics*, Galen's *On the Opinions of Plato and Hippocrates*, Pappus' *Collection* (book 6) and Anthemius' *On Burning Mirrors*; for an overview of ancient optics, see M. Smith 1999: 11-22.

[387] Netz 1999 supplies a cognitive history that tracks the emergence of the diagram and the set of practices that govern it. For more general accounts of Greek mathematics, see Heath 1921, 1931; Lloyd 1973: 33-74; Cuomo 2001.

[388] Cf. Fowler 1987 for a few select papyrological sources.

Authors make references to diagrams as far back as the fifth century BCE,[389] and these mathematical images were so integral to geometrical argumentation that Plato classifies geometers as "those who make diagrams,"[390] while Aristotle treats their construction as the quintessential act of mathematics.[391] Moreover, diagrams play a particularly heightened role in ancient geometrical works, since the proofs therein most often require the presence of an associated image, without which the proposition would be incomprehensible and underdetermined.[392]

The manuscript tradition shows mathematical texts replete with figures and images appearing either within the columns of text or in the margins beside them,[393] and in many ways, these diagrams resemble our own. Ancient geometers draw circles, squares, lines and points and use letters to label them. The problem is, of course, that the transmission of these diagrams is not always reliable and images can be altered, whether through standardization, elaboration or simple ineptitude.[394] Therefore, although manuscript images can provide templates for the diagrams likely to have accompanied proofs, the geometry of each proposition must ultimately guide the reconstruction of any

---

389 Simplic. *In phys.* 53 provides excerpts from Hippocrates of Chios' *Quadrature of the Lunules*, which repeatedly refers to διαγράμματα. Netz 1999: 272-275 argues that while earlier diagrams certainly must have existed, this is one of the earliest that takes the form of an axiomatic-deductive proof; cf. Netz 2004; Weitzmann 1970: 47; Bethe 1964: 116, n. 2.

390 Pl. *Euth.* 290C.

391 Arist. *Cael.* 279b33; cf. *Metaph.* 1051a22-31.

392 Netz 1999: 19-26 articulates the mutual dependence of mathematical texts and their accompanying diagrams; cf. Saito 2006. Similarly, Knorr 1975: 72 deals with the use of γράφειν to indicate "to prove by a diagram," and he ultimately concludes that diagrams "were not mere accessories to mathematical arguments; their purpose was to make evident the truth of the theorem under investigation."

393 Cf. Bethe 1964; Paris suppl. gr. 607, gr. 2442.

394 While individual scribes can mislabel or omit letters entirely, while also displacing lines or even entire proofs, general diagrammatic practices seem to remain relatively consistent within the manuscript tradition.

relevant figure.[395] Still, certain stable features help us exclude particular diagrammatic practices with some degree of probability. For instance, ancient authors do not seem to have employed properly perspectival and three-dimensional renderings; diagrams were often schematic rather than directly proportional;[396] and many (although not all) were produced without the aid of a ruler and compass.[397] Plato may echo these practices when Socrates remarks in the *Republic* that the actual diagram has no intrinsic interest, since it merely serves as a guide for abstract reasoning, which values the ideal figure over the drawn image.[398] Aristotle promotes a similar position, asserting: "The geometer draws no conclusions on grounds of the lines he names, but rather draws conclusions on the basis of the things made clear by them" [ὁ δὲ γεωμέτρης οὐδὲν συμπεραίνεται τῷ τήνδε εἶναι γραμμὴν ἣν αὐτὸς ἔφθεγκται, ἀλλὰ τὰ διὰ τούτων δηλούμενα].[399] For ancient authors, then, diagrams were not necessarily precise representations, but abstract tools

[395] Cf. Netz 1999: 12.

[396] Cf. Jones 1986; Netz 1999: 18-19. By way of comparison, in the Hellenistic period, technical manuals—such as *mechanics, belopoiics*, *poliocetics* and *pneumatics*—would have contained illustrations, and from manuscript evidence, illustrators often seemed to have sacrificed realistic depiction in order to make a particular mechanism clear within the confines of the two-dimensional drawing space (e.g. the top of a cylinder might be depicted as elliptical to indicate its potential volume, while the bottom of the same cylinder might be represented as flat in order to illustrate an attached valve mechanism more easily (see Weitzmann 1971: 21-24 for plates; cf. Netz 1999: 18; van Leeuwen 2012: 74). Precision and accuracy of representation were subservient to the main goal of the diagram, which was comprehensibility. For an account of mechanical drawings in antiquity, see Drachmann 1963, while for broader surveys of Greek scientific illustrations, see Bethe 1964: 22-40; Weitzmann 1977: 20-44.

[397] This is a matter of some debate. Netz 1999: 17 argues that there is good papyrological evidence for the use of rulers in diagram construction, citing plates in Fowler 1987. An examination of the plates themselves, however, shows the evidence to be split. My own evaluation of manuscripts suggests that scribes are more likely to use a ruler and compass when copying a strictly mathematical work, such as Euclid's *Elements*, than when copying a (scientific) work that includes some geometrical arguments, such as Aristotle's *Meteorologica* or *Mechanica*; cf. Louis 1988: *xxxv*; van Leeuwen 2012: 80-85, 133-227.

[398] Pl. *Rep.* 510d5-511a1; cf. *Euthyd.* 290b10-c6. This obviously fits in with a larger Platonic epistemology. At *Meno* 82b6-85e5, Plato considers diagrams to be invaluable "aids" to discovery; cf. *Phaedr.* 73a6-b2l; cf. Fowler 1987: 3-29.

[399] Arist. *An. post* 77a1-3.

that helped the mind gain access to immaterial geometrical properties—at least, that is how they were supposed to be used.

In operation, diagrams functioned in a slightly different way, especially in the case of applied mathematics. In these instances, because the subject of inquiry was no longer abstract, ancient authors needed to translate physical objects into entities comprehensible within diagrammatic space.[400] As a result, authors reformulated and reconstructed experiences according to a new set of rules and priorities. Both the world and its objects became mediated through the practices of geometry. The new mathematical entities created in this process often operated with what I will call "hybrid ontologies,"[401] insofar as they are supposed to be representations of physical things, but the properties that those things are assumed to display *outside* the diagram are bound up with their geometrical construction *within* it. That is, these diagrams cannot truly be representations or abstractions, since they construct the entities that they portray as much as they represent them. In other words, by making certain mathematical arguments possible, the diagrams make certain physical arguments possible. They simultaneously inform and embody assumptions about how the physical phenomena work and in the process activate arguments in both realms. They possess dual-citizenship, so to speak. When authors need these representations to be abstractions, the treat them as such; yet, authors also derive assumptions from the diagrams as if they were pictures of real physical things, not mathematically useful constructions. Thus, a diagram is not simply a

[400] Asper 2009: 117 notes that the treatment of physical phenomena with mathematics (i.e. applied geometry) is deeply influenced by the practices governing theoretical geometry.

[401] I am borrowing this vocabulary from Dick 2014, who uses the concept of "hybrid ontologies" to discuss how abstract representations of "linked list" computer code relate to the machines that embody these calculations.

site where theories find their expression, but a set of material practices that creates a physical heuristic.

4.1 Aristotle's Optics

In book 3 of the *Meteorologica*, Aristotle investigates several celestial phenomena, including the halo, the mock sun and rods.[402] The longest part of this investigation, however, concerns the rainbow. In order to begin his explanation of it, he provides a list of "accompanying facts" [τὰ συμβαίνοντα][403] for which he will account.[404] These include: 1) why the rainbow is never a full circle, but only ever a segment of a semi-circle;[405] 2) why rainbows will never occur at or around midday during the summer months; 3) why no more than two rainbows can occur at the same time; and 4) why rainbows display three and only three colours—and always in the same order: red, green and blue.[406] Although Aristotle includes multiple physical arguments, the core of his explanation rests on several geometrical proofs in which he traces the rectilinear propagation of sight [ὄψις].[407] The problem, however, is that whereas both *De anima* and *De sensu* attribute vision to qualitative alteration through the transparent, the arguments in the *Meteorologica* seem to commit Aristotle to some version of an extramissionist

---

[402] For the most recent discussion of Aristotle's *Meteorologica*, see Wilson 2013. For a more general account of ancient meteorology, see Taub 2003.

[403] Freeland 1990 examines Aristotle's use of συμβαίνοντα as part of his general endoxic practice; cf. Owen 1986; Nussbaum 1987; Freeland 1990; R. Smith 1995; Frede 2004; C. Long 2006. For an account of the rise of συμβαίνοντα in the methodology of post-Aristotelian science, see Sedley 1982.

[404] Arist. *Mete*. 371b27-372a17.

[405] He also adds that as the sun rises in the sky, the circle the rainbow *would* complete becomes larger, even though the visible segment of this circle decreases; cf. Arist. *Mete.* 375b25-29.

[406] If a second, double rainbow appears, Aristotle argues, the order of these colours will be reversed; Arist. *Mete.* 374b35-375b15.

[407] These are the earliest extant diagrams to depict sight in this way.

theory, and this contradicts what he has already advocated. This discrepancy has led some scholars to reject the *Meteorologica*'s authenticity, either in part or in whole,[408] but several other Aristotelian works reference the treatise, which make this argument difficult to uphold.[409] What are we to do with this tension? Is there a way to make sense of this inconsistency? I would like to suggest that Aristotle's use of geometry to explain the rainbow draws him into 'thinking with lines,' thus facilitating the adoption of a ray-theory as a physical heuristic. The thin marks on the page provide useful cognitive tools with which he can draw certain extra-mathematical conclusions.

Before examining these assertions in greater detail, however, we should look at how geometrical practices affect his conceptions of the other entities responsible for the production of a rainbow. His account begins by asserting that the same cause explains all the accompanying facts mentioned above: they all occur because the rainbow results from reflection.[410] Indeed, rainbows always appear opposite the sun and so, according to Aristotle, must be caused by a reflective surface located somewhere in that region of the sky.[411] Since mist and clouds generally occupy this position, Aristotle assumes that their component parts (i.e. raindrops) constitute the required surface and that each raindrop acts as a tiny mirror—especially when moisture is just in the process of transitioning

[408] For instance, Jones 1994 argues against the authenticity of the geometrical section, but his conclusion is not widely accepted.

[409] Cf. Cappelle 1912, 1935. The authenticity of the *Meteorologica* excludes book 4, which has long been considered inauthentic; cf. Gottschalk 1961.

[410] Arist. *Mete.* 372a18-21. Aristotle asserts that mock suns and rods are also caused by reflection; cf. *Mete.* 373a32-34. The idea that the rainbow was caused by reflection had been around since at least Anaxagoras (cf. DK 59 A 86, 59 B 19), and it was also shared by Plato's contemporary, Philip of Opus; see Alex. Aphr. *In meteor.* 151.32-152.16; cf. Tarán.1975: 118, 135.

[411] Arist. *Mete*. 373b16-25; cf. 373b34-35. The diagram at *Mete.* 375b19-29 operates with this assumption as well.

from mist into water.[412] Because of their proximity, these individual mirrors act as a single unit, forming a cohesive and contiguous magnitude [ἡ συνεχεία τοῦ μεγέθους].[413] Aristotle then proceeds to use this reflective surface to explain the rainbow's distinctive shape, making no further claims about the physical world or the clouds. Instead, he simply draws a diagram (fig. 11):

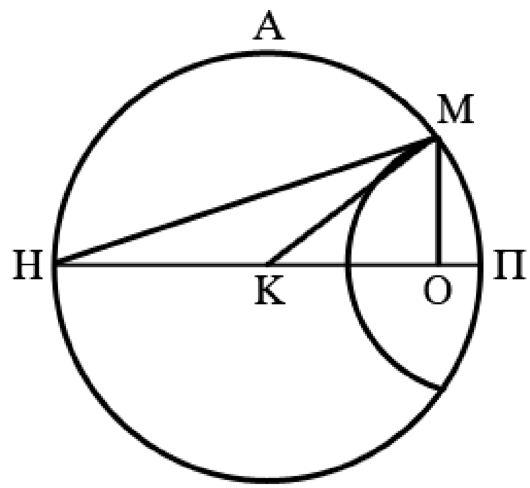

Fig. 11 Aristotle's Rainbow (*Mete.* 375b19-29)

> ἡμισφαιρίου γὰρ ὄντος ἐπὶ τοῦ ὁρίζοντος κύκλου τοῦ ἐφ' ᾧ τὸ Α, κέντρου δὲ τοῦ Κ, ἄλλου δέ τινος ἀνατέλλοντος σημείου ἐφ' ᾧ τὸ Η, ἐὰν ἀπὸ τοῦ Κ γραμμαὶ κατὰ κῶνον ἐκπίπτουσαι ποιῶσιν ὡσπερεὶ ἄξονα τὴν ἐφ' ᾗ ΗΚ, καὶ ἀπὸ τοῦ Κ ἐπὶ τὸ Μ ἐπιζευχθεῖσαι ἀνακλασθῶσιν ἀπὸ τοῦ ἡμισφαιρίου ἐπὶ τὸ Η ἐπὶ τὴν μείζω γωνίαν, πρὸς κύκλου περιφέρειαν προσπεσοῦνται αἱ ἀπὸ τοῦ Κ· καὶ ἐὰν μὲν ἐπ' ἀνατολῆς ἢ ἐπὶ δύσεως τοῦ ἄστρου ἡ ἀνάκλασις γένηται, ἡμικύκλιον ἀποληφθήσεται τοῦ κύκλου ὑπὸ τοῦ ὁρίζοντος τὸ ὑπὲρ γῆν γιγνόμενον, ἐὰν δ' ἐπάνω, ἀεὶ ἔλαττον ἡμικυκλίου· ἐλάχιστον δέ, ὅταν ἐπὶ τοῦ μεσημβρινοῦ γένηται τὸ ἄστρον.
>
> If there is a hemisphere on the circle of the horizon on which A is placed, and the hemisphere's centre is K, and if there is some other point, on which H is placed, which can rise upwards—in this case, if written lines

[412] This is because, as Aristotle states at *Mete.* 373a35-b1, "It is apparent that vision is reflected from all smooth surfaces, among which both air and water are included" [ἀνακλωμένη μὲν οὖν ἡ ὄψις ἀπὸ πάντων φαίνεται τῶν λείων, τούτων δ' ἐστὶν καὶ ἀὴρ καὶ ὕδωρ]; cf. *Mete.* 372a32.

[413] Arist. *Mete.* 373b27. Moreover, because the drops are so small, they cannot reproduce the sun's shape alone and instead only reflect the sun's colour; cf. *Mete.* 372a29-34.

> projecting from the centre along a cone make the line HK an axis, as it were, and the lines joined from K to the M are reflected back from the hemisphere to the H on the greater angle, the lines from K project to the circumference of a circle. And if the reflection occurs at the rising or the setting of the heavenly body, the semicircle that is below the earth will be cut off by the circle of the horizon, but if it is higher, it will always be less than a semi-circle; and it will be smallest when the heavenly body reaches the meridian (Arist. *Mete.* 375b19-29).

In this diagram, the viewer is placed at the centre of a hemisphere that rests on the visible horizon. Aristotle then describes a line which projects from the viewer, strikes the hemisphere at point M and then reflects back to the celestial light source (presumably the sun) at point H. He then goes on to say that because this reflection takes place on a hemisphere, when you swivel the ray of vision around the centre axis, it produces a series of similar triangles along a single arc. Then, although he does not provide it, Aristotle proposes that there is some special ratio between the distance of the viewer to the reflective hemisphere (line KM) and from the reflective hemisphere to the sun (line MH), which governs where the rainbow will occur.[414]

There are multiple questions that Aristotle's explanation evokes, especially since the diagram does not easily harmonize with any plausible physical picture. One might naturally assume that the hemisphere (or at least the part that reflects) represents the mist

---

[414] Arist. *Mete.*375b30-376b23. Since the visual ray in the diagram projects from the viewer at the centre of the circle, it would hit the reflective sphere perpendicular to the tangent. Consequently, the ray should not actually reflect towards the sun at H as is pictured, but, according to the law of reflection, should reflect directly back towards the viewer at K. Boyer 1946, Pedersen 1973: 113 and Stothers 2009 all think that Aristotle knew the law, but the first reference to a law of reflection does not appear until [Arist.] *Pr.* 11.23.901b21-23; 16.13, 915b18-35 (although this text and its *lemmata* are hard to date with any precision). Philip of Opus reportedly argued that rainbows occurred by reflection, which might suggest that the law was known, but he supports his argument by stating that the rainbow appears to follow you as you walk side to side; cf. Alex. Aphr. *In meteor.* 151.32-152.16; cf. n. 385 and 451. Of course, unless the mirrored surface moves in perfect co-ordination with your movements, according to the law of reflection, the rainbow should *not* follow you, but move in the opposite direction. Thus, Philip's arguments are actually slight evidence against accepting that the law of reflection was known—although it is also possible that he knew it and simply misapplied it. Nevertheless, following Merker 2002, we should not consider Aristotle's ratio a replacement *law* of reflection, since it is somewhat revisionist to presume that Aristotle was trying to articulate a law in the first place. Still, Aristotle grants the length of his reflecting rays to *some* given ratio, even if it is not to be considered a universally applicable proportion.

of the clouds, but as natural as this interpretation may be, clouds do not ostensibly form a hemisphere over the entirety of the sky, nor do they appear to be perfectly concave. The diagram also places the rainbow at the very edge of our visible horizon (even though earthly objects often appear *behind* rainbows) and places the sun and the clouds at equal distances from the viewer (even though Aristotle's own theories about the celestial spheres and the sub-lunar realm, some of which are displayed at the very beginning of the *Meteorologica* itself,[415] preclude this possibility). In order to address these problems, Boyer suggests that the diagrams are not designed to be directly representational, but simply present the kind of explanation that *would* provide a causal account.[416] This is not, however, what Aristotle claims when he introduces his figure and articulates its status:

> ὅτι δ' οὔτε κύκλον οἷόν τε γενέσθαι τῆς ἴριδος οὔτε μεῖζον ἡμικυκλίου τμῆμα, καὶ περὶ τῶν ἄλλων τῶν συμβαινόντων περὶ αὐτήν, ἐκ τοῦ διαγράμματος ἔσται θεωροῦσι δῆλον.
>
> That it is not possible for a circle of a rainbow to occur, nor a segment greater than a semicircle—these and all the other accompanying facts will be clear from the diagram to those looking at it (Arist. *Mete.* 375b16-19).[417]

According to this particular passage, a diagram "makes clear" the essential facts of the matter at hand. What is more, in the *Posterior Analytics* Aristotle uses the rainbow as the paradigmatic example of a physical phenomenon for which geometry can provide a causal explanation: he states that a natural philosopher [φυσικός] knows *that* [ὅτι] a

[415] Arist. *Mete.* 339b4-341a13. Lee 1968: 24-27 also sees the problem with this physical picture and provides a 'Note on the Strata' alongside these remarks of Aristotle to show their incompatibility; cf. Knorr 1986: 107, who calls the meteorological hemisphere "patently absurd from a cosmological standpoint."

[416] Boyer 1959: 42.

[417] Knorr 1975: 72 claims that this statement shows that Aristotle considers his diagrams to make clear the *theorem* under question, but the above passage suggests that they make clear the συμβαίνοντα.

rainbow occurs, but the optical scientist [ὀπτικός] must know *why* [διότι] it occurs.[418] For Aristotle, then, his diagram "makes clear" the rainbow's characteristics by providing a causal account.[419] It does not merely show the *type* of explanation that would be necessary; it is supposed to demonstrate the actual mechanism itself.

If Aristotle is demonstrating the actual cause of the rainbow, however, what exactly is he drawing? Although the geometry relies on an apparently impossible physical situation, several details suggest that Aristotle still intends his diagram to be a physical model at least of some kind. For example, the very lettering that he has chosen evokes physical entities: whereas K seems to stand for κέντρον, the geometrical "centre," H seems to stand in for ἥλιος, "sun," and M for μέλαν, "black" or "black cloud."[420] Moreover, Aristotle talks about the ground [γῆ] cutting off the visible part of the rainbow, not simply the geometrical horizon.[421] Yet, Aristotle is not just presenting a poorly executed picture of the world, since the hemisphere does not really represent the clouds as much as it *stands in* for them. In other words, he constructs a metonymic physical world for the rainbow to inhabit. Aristotle's geometrical picture cannot be

---

[418] Arist. *An. Post.* 79a11-13: "Just as the subject concerning the rainbow: for it belongs to the natural philosopher to know *that* it occurs; but it belongs to the optical scientist to know *why* it occurs, either simply or according to a learned account" [οἷον τὸ περὶ τῆς ἴριδος· τὸ μὲν γὰρ ὅτι φυσικοῦ εἰδέναι, τὸ δὲ διότι ὀπτικοῦ, ἢ ἁπλῶς ἢ τοῦ κατὰ τὸ μάθημα]. This passage has been subject to some disagreement, especially as regards the meaning of ἢ ἁπλῶς ἢ τοῦ κατὰ τὸ μάθημα; cf. Barnes 1975: 149; Brunschwig 1983; W.D. Ross 1949: 555. More recently Merker 2002: 227-228 has suggested that κατὰ τὸ μάθημα cannot be a mathematical account, which would be κατὰ τὴν ὄψιν, but even if we take the former phrase to denote a "learned account," I see no need to preclude geometry as an integral part of an optical scientist's explanation.

[419] Cf. Arist. *Meta.*981a28-30, which defines a technician as someone who can provide a casual account of a phenomenon, i.e. explain 'why' [διότι] it happens. In contrast, at *Cael.* 279b33-280a11 Aristotle considers diagrams to be teaching aids.

[420] For these significations of the letters, see Louis 1982: 20, n.5. Van Leeuwen 2012: 73 notes that letters in diagrams, even in applied geometrical texts, rarely stand for fixed objects (e.g. *d* for *diameter*, or *h* for *height*), with the one exception being K for κέντρον.

[421] Arist. *Mete.* 375b28.

considered an abstraction of a theory, since no such theory *can* exist independently of the geometric parameters that the diagram provides. The diagram thus opens up a conceptual space that becomes the rainbow's proper site—where causes are discerned and where validity is granted. In this sense, the diagram is not truly an *abstraction* of a physical model; it *is* a physical model, but the world now resides within its boundaries. Although it differs from an analogy with a material tool, this diagram provides another instance where a technology operates as a type of physical theory.

Even if the physical world has been transplanted into it, Aristotle's geometrical image still allows for certain physical arguments to be made outside its borders. In one sense, this is not surprising, since the explanatory power of geometry is precisely why authors employ diagrams to understand phenomena in the first place. Yet, it is not simply arguments that are exported, but the geometrical entities themselves, which end up operating with our so-called hybrid ontologies. That is, the lines on the page activate claims in both the mathematical and natural realms. For instance, without being translated into geometrical space clouds could potentially be considered puffy and billowing, but now they are assumed to be smooth and perfectly shaped—even in the world outside the diagram. When they reflect sight from the viewer and produce new colours in the process, they do so with a perfectly concave surface. Despite any visual evidence to the contrary, theorists can now simply take for granted that clouds are hollow. Because the geometry requires it, it becomes a physical assumption. In other words, the entities within the diagram construct ideas about the physical world outside of it. In fact, this physical argument was persuasive enough to be canonized within the meteorological tradition, assumed as patently true by multiple authors, for whom the lines on the page were reified into objects in the world.[422] For our present purposes, however, it is more important to interrogate how the "written lines" [γραμμαί] work in relation to eyesight. Are they supposed to stand in for real physical entities, or are they simply analytic tools? How do we account for the fact that they seem to suggest an extramissionist account, even though this conflicts with what Aristotle states elsewhere?

As early as Alexander of Aphrodisias, commentators have tried to smooth over any inconsistency by suggesting that Aristotle's description is only a manner of speaking—an analytic rather than a representational account.[423] To be sure, Aristotle keeps his physical and geometrical language separate in regards to the visual ray—that is, he talks about "written lines" while discussing the diagram but uses "sight" or "visual ray" [ὄψις] when referring to its physical implications.[424] Yet, in the proof itself, Aristotle refers to these γραμμαί projecting from the viewer at K *to* the hemisphere at M and then from the hemisphere *to* the sun at H. He later repeats a similar claim, stating: "it is clear, then, that the rainbow is a reflection of sight [ὄψις] *towards the sun*."[425] Describing sight as projecting from the viewer to the sun looks suspiciously like an extramissionist model of eyesight. Other details confirm this. For example, he describes a man who used to see his own image constantly reflected back to himself. Aristotle attributes this to the man's sight being too weak to push through the open air.

---

[422] For examples, see Sen. *NQ* 1.5.13 (who mentions that Posidonius held this opinion as well); Lucr. *DRN* 6.189-203; Plin. *NH* 2.60.151; Alex. Aphr. *In meteor*. 139.6-18.

[423] Alex. Aphr. *In meteor.* 141.2. Similarly, some modern commentators follow Alexander in arguing that Aristotle is simply bending to contemporary vocabulary of visual rays; cf. Boyer 1959: 50; Gottschalk 1964b: 79-80; G. Simon 1988: 48-51; M. Smith 1999: 150. For his part, Gal. *De plac. Hipp. et Plat.* 7.7.11-13 simply chastises Aristotle for being inconsistent (although Galen himself succumbs to this same inconsistency).

[424] Cf. Merker 2002: 237.

[425] Arist. *Mete.* 373b33-34.

> γίγνεται δὲ ἀπὸ μὲν ἀέρος, ὅταν τύχῃ συνιστάμενος. διὰ δὲ τὴν τῆς ὄψεως ἀσθένειαν πολλάκις καὶ ἄνευ συστάσεως ποιεῖ ἀνάκλασιν, οἷόν ποτε συνέβαινέ τινι πάθος ἠρέμα καὶ οὐκ ὀξὺ βλέποντι· ἀεὶ γὰρ εἴδωλον ἐδόκει προηγεῖσθαι βαδίζοντι αὐτῷ, ἐξ ἐναντίας βλέπον πρὸς αὐτόν. τοῦτο δ' ἔπασχε διὰ τὸ τὴν ὄψιν ἀνακλᾶσθαι πρὸς αὐτόν· οὕτω γὰρ ἀσθενὴς ἦν καὶ λεπτὴ πάμπαν ὑπὸ τῆς ἀρρωστίας, ὥστ' ἔνοπτρον ἐγίγνετο καὶ ὁ πλησίον ἀήρ, καὶ οὐκ ἐδύνατο ἀπωθεῖν—ὡς ὁ πόρρω καὶ πυκνός·
>
> [A reflection] occurs in air whenever it happens to be compressed. Often it can cause a reflection even without compression, because of the weakness of sight. Such a thing used to happen to someone who saw softly and not sharply. For an image always used to precede him as he walked, staring back at him opposite. He experienced this because *his sight was reflected back to him*. *For it was altogether so weak and thin from feebleness* that even the nearby air became a mirror, and *his sight was unable to push through it* (Arist. *Mete.* 373a35-b9, emphasis mine).

If sight has the capacity to thrust through mist, it must be some type of physical substance. Moreover, by describing the weakness of sight to its thinness, Aristotle seems to be indicating that it has some type magnitude or density. He intimates similar ideas when describing how sight degrades as it stretches out, which causes a shift in colour towards darkness. Sometimes sight does not reach objects at all.[426] To be sure, if sight cannot reach its objects, some visual substances must proceed *from* the eye, and the most likely candidate for this substance is a type of visual ray.[427] Therefore, just like the sun and the black clouds, the lines projecting from the viewer in the diagram must also stand

[426] Arist. *Mete.* 474b9-15.

[427] We could conceivably take ἐλάττων as figurative, but accompanying physical details suggest a more literal reading. Jones 1994: 63 makes a similar set of observations and insists that Aristotle subscribes to a physical visual-ray model. Jones also adds that the ray must be fiery since watery eyes are bad for vision; cf. Merker 2002: 195 for support.

in for some physical entity—even if this entity is bound up with its articulation in geometrical space.[428]

Why does Aristotle think about vision in terms of linear rays projecting from the eyes precisely when he uses diagrams to explain optical phenomena? Perhaps phrased like this, the answer to the question becomes obvious. Within the diagrammatic space, 'qualitative alterations' [ἀλλοίωσις] are not comprehensible. Instead, they need to be translated into geometrically sanctioned entities. Just as Aristotle conceptualizes clouds as a hemisphere in order to inscribe them within a set of mathematical technologies, he re-configures eyesight in the same way—that is, if he really is *translating* his previous theory. It is entirely possible that the diagram and the mathematical proof simply facilitate adopting different arguments about vision, even though they conflict with his views elsewhere. To be sure, it seems unlikely that Aristotle *first* changed his mind, deciding that rays were the mechanism of vision rather than qualitative alterations, and only *then* realized that he could abstract rays geometrically to explain the rainbow, halo, mock suns and rods. To my mind, it seems more likely that the geometrical articulations of these meteorological phenomena first proved useful and persuasive, and then, just as with the clouds, a similar type of metonymy occurred for sight. As a result, the lines on the page presented a visible heuristic that allowed Aristotle to adopt new physical arguments and activate certain physical claims.[429]

---

[428] Arist. *Phys.* 194a7-12 claims that the optical scientist studies mathematical lines, but *qua* physical entities rather than *qua* mathematical; this stance increases the likelihood that the ὄψις in the diagram represents physical entities.

[429] That being said, the behaviours Aristotle attributes to the visual rays outside of the diagram sit in slight tension with their geometrical counterparts, since geometrical lines do not degrade or shrink over distance, and it would be hard to consider one line 'strong' and another 'weak.' In this way, when deployed in the world, geometrical entities can take on new characteristics. Still, the very presence of a visual ray theory in Aristotle's text is bound up with the needs of his meteorological arguments and their geometrical

If diagrams had this affect on Aristotle's theory of vision, how did they shape optical theories more generally? How do extramissionist accounts relate to this technology? To be sure, geometrical renditions of vision did not produce the idea that something exits the eye. For instance, I have already discussed how Empedocles posits that fire streams from the pupils, and an extramissionist impulse date backs to at least the Pythagoreans, who are said to have compared reflection to a hand that reaches out to its object before bending back at the elbow to touch the shoulder.[430] This formulation figures vision as a type of touch, able to exit the eye and 'grasp' its objects. That being said, it lacks the strict mathematical linearity of later theories, since it relies on a simple appendage-like extension that may or may not be perfectly straight. Plato, however, commits more fully to a properly rectilinear theory in the *Timaeus*, where the stranger proposes that a "current of sight" [τὸ τῆς ὄψεως ῥεῦμα] issues forth from the eye "along the straight line of the eyes" [κατὰ τῶν ὀμμάτων εὐθυωρίαν]. In this account, the visual stream is composed of an internal fire, which flows out from the eyes and meets the "sibling" substance of daylight. When something touches the stream combined of the two, a motion is transferred back to the soul. In the *Timaeus*, the stranger describes it as follows:

articulation. The *Meteorologica*, however, is not the only place that Aristotle employs a visual ray theory of vision. At *GA* 781a3-13, he also states that those animals with recessed eyes see distances better, since the hollowed brow concentrates the visual motion and does not let it scatter. Similarly, at *Cael*. 290a13-23 he claims that the sun looks bigger near the horizon because "when it is extended out, sight shakes because of its great weakness" [ἡ γὰρ ὄψις ἀποτεινομένη μακρὰν ἑλίσσεται διὰ τὴν ἀσθένειαν]. He attributes the twinkling of the stars to a similar cause. In these passages, Aristotle ultimately expresses ambivalence towards the intromissionist/extramissionist debate, saying it makes no difference which of the two theories you support. Despite Aristotle's claims, however, deciding between these theories does matter for the validity of his physical arguments, especially for those in the *Meteorologica*, where he adopts an extramissionist account more fully.

430 Aët. 4.14.3; cf. Jones 1994, who provides a history of visual ray-theories in the Peripatetic tradition.

τῶν δὲ ὀργάνων πρῶτον μὲν φωσφόρα συνετεκτήναντο ὄμματα, τοιᾷδε ἐνδήσαντες αἰτίᾳ. τοῦ πυρὸς ὅσον τὸ μὲν κάειν οὐκ ἔσχε, τὸ δὲ παρέχειν φῶς ἥμερον, οἰκεῖον ἑκάστης ἡμέρας, σῶμα ἐμηχανήσαντο γίγνεσθαι. τὸ γὰρ ἐντὸς ἡμῶν ἀδελφὸν ὂν τούτου πῦρ εἰλικρινὲς ἐποίησαν διὰ τῶν ὀμμάτων ῥεῖν λεῖον καὶ πυκνὸν ὅλον μέν, μάλιστα δὲ τὸ μέσον συμπιλήσαντες τῶν ὀμμάτων, ὥστε τὸ μὲν ἄλλο ὅσον παχύτερον στέγειν πᾶν, τὸ τοιοῦτον δὲ μόνον αὐτὸ καθαρὸν διηθεῖν. ὅταν οὖν μεθημερινὸν ᾖ φῶς περὶ τὸ τῆς ὄψεως ῥεῦμα, τότε ἐκπῖπτον ὅμοιον πρὸς ὅμοιον, συμπαγὲς γενόμενον, ἓν σῶμα οἰκειωθὲν συνέστη κατὰ τὴν τῶν ὀμμάτων εὐθυωρίαν, ὅπῃπερ ἂν ἀντερείδῃ τὸ προσπῖπτον ἔνδοθεν πρὸς ὃ τῶν ἔξω συνέπεσεν ὁμοιοπαθὲς δὴ δι' ὁμοιότητα πᾶν γενόμενον, ὅτου τε ἂν αὐτό ποτε ἐφάπτηται καὶ ὃ ἂν ἄλλο ἐκείνου, τούτων τὰς κινήσεις διαδιδὸν εἰς ἅπαν τὸ σῶμα μέχρι τῆς ψυχῆς αἴσθησιν παρέσχετο ταύτην ᾗ δὴ ὁρᾶν φαμεν.

Of the organs, [the superiors] first constructed the light-bearing eyes, fixing them [in the front of the head] for the following reason. They contrived a body of fire—not enough to burn, only to provide gentle light, similar to that of each day. For they made the pure fire inside of us (which is a sibling to this) flow through the eyes, and they made the whole substance smooth and dense, especially compressing the middle of the eyes, so as to keep out any other, coarser fire entirely, and to allow only this pure type of fire to filter through. And so whenever midday light surrounds the current of sight, at that time like falls upon like, coalescing together, and establishing one kindred body along the straight line of the eyes, wherever that which falls forward from within exerts pressure against that which falls against it from without, becoming entirely similar of quality because of their similarity; and wherever at any time something touches this and is touched by it, it distributes their motions into the entire body until it reaches the soul, and it provides this perception which we call 'seeing' (Pl. *Tim*. 45b2–d3).[431]

Plato's visual stream operates in different ways at different times. At one moment, it resembles a fluid, as the pupil sifts larger particles out of the stream flowing through the eye. At another moment, the stream takes on the characteristics of fire, as it coalesces with the daylight. At other moments still, it resembles a solid body, able to transmit sensation backwards while running in a straight line. In other words, the basic extramissionist concept is quite flexible and can fill multiple roles—even within the same

[431] Cf. Pl. *Tim*. 67c4-68d6.

author's account. Plato's theory is therefore not *per se* incompatible with a mathematical articulation of a visual ray, but it is not identical. Indeed, neither a stream of fire, nor a hand-like extension is quite identical to a visual ray. What can be said, however, is that all of these non-geometrical accounts construe sight as a *single* extension, continuing along a *single* straight line. In the next section, I will discuss how geometrical representations of vision help reformulate extramissionist theories around the idea that multiple lines leave the eye, collectively comprising a visual cone. Even if diagrams did not create extramissionist ideas, visual ray-theories coalesced around the geometrical treatment of sight.

4.2 Euclid's *Optics* and Hybrid Ontology

Whereas Aristotle's *Meteorologica* dealt with vision as an incidental feature within a larger meteorological investigation, the *Optics* attributed to Euclid (*fl. c.* 300 BCE) is a fully geometrical treatment of sight.[432] This latter text—the most foundational treatise in the optical tradition—does not provide speculations about the physiology of the eye, or concern itself with articulating any explicit physical theory. Instead, it establishes seven definitions [ὅροι], which are then employed in a series of fifty-seven geometrical propositions. As such, the *Optics* bears much more in common with the

[432] There are two different versions of the *Optics* preserved in the manuscript tradition, now referred to as version A and version B (cf. Jones 1994). After the publication of Heiberg 1882, edition A was considered to be the authentic Euclidian text, while B (also referred to as the *Recensio Theonis*) was thought to have been an edition produced by Theon of Alexandria (*c*. 335-*c*. 405). Knorr 1991 and Jones 1994 both have argued against Heiberg's assumptions and shown version B to be the older text. I adopt their arguments and use manuscript B as the main text for investigation (cf. M. Smith 1999)—although I will refer occasionally to manuscript A as well. That being said, both Knorr and Jones insist that many passages of the B manuscript may still be interpolations, concerns which call into question to what degree we can consider Euclid the text's sole author. Thus, although I will refer to "Euclid" in this chapter, I have elsewhere referred more obliquely to the "Euclidian author" to avoid making a definitive claim in regards to the text's full authenticity; cf. Webster 2014.

Elements, than it does with either Aristotle's *De sensu et sensibilibus* or Theophrastus' *De sensu*. Devoid of physical explanations, the *Optics* makes the diagram the sole tool through which vision is articulated. In fact, the distinctly mathematical nature of the text has long made commentators question whether any physical theory lurks behind its diagrams at all. For instance, even in antiquity, Geminus argued that optics displays complete indifference to the physical workings of vision:

> ὅτι οὔτε φυσιολογεῖ ἡ ὀπτικὴ οὔτε ζητεῖ, εἴτε ἀπόρροιαί τινες ἐπὶ τὰ πέρατα τῶν σωμάτων φέρονται ἀπὸ τῶν ὄψεων ἀκτίνων ἐκχεομένων…μόνον δὲ σκοπεῖ εἰ σώζεται καθ' ἑκάστην ὑπόθεσιν ἡ ἰθυτένεια τῆς φορᾶς ἢ τάσεως καὶ τὸ κατὰ τὴν συναγωγὴν εἰς γωνίαν τὴν σύννευσιν γίνεσθαι, ἐπειδὰν μειζόνων ἢ ἐλαττόνων ὄψεως ᾖ θεωρία.
>
> Optics neither investigates the physical nature of vision, nor seeks to know whether certain emanations are carried to the edges of bodies by means of rays flowing out from the eyes…It only examines whether the straightness of the motion or extension in each hypothesis is preserved and if the convergence [of the rays] into an angle at their meeting point is preserved whenever the eye beholds something greater or smaller (Geminus, *Frag. Opt.* 24).[433]

Modern interpreters have long echoed Geminus' interpretation by investigating solely whether Euclid's propositions were compatible with ideas of linear perspective.[434] The dominance of this single question led even opposing scholars to treat Euclid as though he were presenting an analytic explication of perspective.[435]

---

433 Cf. Jones 1994: 47-48, who suggests that Alex. Aphr. *In meteor.* 1.27-28 promotes an analytic reading of the *Optics*. A full survey of Alexander's arguments in the section, however, suggests that he believes the mathematicians endorse a physical visual ray theory; cf. Alex. Aphr. *In meteor.* 141.2, who takes issue with the physical nature of the mathematicians' ἀκτῖνες. See also Berryman 1998, who also takes Alex. Aphr. *In de sensu* 27.27-28.15 to indicate Alexander's physical interpretation of Euclid's rays.

434 Brownson 1981 claims that the angular basis of Euclid's optics is compatible with the modern linear perspective as it was developed in Renaissance art; cf. Tobin 1990. In contrast, Panofsky 1991 argued that the two formulations cannot be harmonized; cf. Knorr 1991.

435 Most recently, Sinisgalli 2012 has also continued this debate, albeit to limited success; cf. Koortbojian 2013.

In response, Simon has devoted considerable energy to historicizing the *Optics*, arguing that it primarily concerns the propagation of *sight* and not, as scholars before him implicitly assumed, the propagation of *light*.[436] More recently, Jones has also illustrated that several of Euclid's definitions rely on a set of physical hypotheses that belie any completely analytic reading of the text.[437] Still, in his account, Jones suggests that the diagrams are used as "abstractions" of physical entities in the world.[438] To be sure, several propositions certainly do betray physical commitments. Nevertheless, the *Optics* cannot truly be presenting an abstraction of a fully formed physical theory, since abstractions would move *from* the world and *into* a conceptual space. Instead, Euclid's physical hypotheses are not independent of the geometrical context in which they appear; they are bound up with the means of their own articulation. In other words, the set of practices that govern diagrammatic space are as much a part of Euclid's physical theory of vision as any prefabricated physical tenets. In sum, his geometrical practices help determine 1) what entities are involved in the process of vision; 2) what type of physical qualities these entities display; and 3) what constitutes a visual appearance in the first place. In this way, the technology that Euclid uses as a cognitive tool controls and regulates his operational definition of vision.

At a basic level, the diagram requires Euclid to translate the compound and amorphous phenomenon of sight into a form that abides by a certain set of mathematical rules. He does this in his seven definitions:

---

[436] G. Simon 1988. Although his is a useful corrective, Simon's formulation does not account for many of the propositions within the *Optics* that do not deal directly with sight; cf. Webster 2014.

[437] Jones 1994; cf. Lindberg 1976: 13; Berryman 1998.

[438] Jones 1994.

α´. ὑποκείσθω τὰς ἀπὸ τοῦ ὄμματος ὄψεις κατ’ εὐθείας γραμμὰς φέρεσθαι διάστημά τι ποιούσας ἀπ’ ἀλλήλων.
β´. καὶ τὸ μὲν ὑπὸ τῶν ὄψεων περιεχόμενον σχῆμα εἶναι κῶνον τὴν κορυφὴν μὲν ἔχοντα πρὸς τῷ ὄμματι, τὴν δὲ βάσιν πρὸς τοῖς πέρασι τῶν ὁρωμένων.
γ´. καὶ ὁρᾶσθαι μὲν ταῦτα, πρὸς ἃ ἂν αἱ ὄψεις προσπίπτωσιν, μὴ ὁρᾶσθαι δέ, πρὸς ἃ ἂν μὴ προσπίπτωσιν αἱ ὄψεις.
δ´. καὶ τὰ μὲν ὑπὸ μείζονος γωνίας ὁρώμενα μείζονα φαίνεσθαι, τὰ δὲ ὑπὸ ἐλάσσονος ἐλάσσονα, ἴσα δὲ τὰ ὑπὸ ἴσων γωνιῶν ὁρώμενα.
ε´. καὶ τὰ μὲν ὑπὸ μετεωροτέρων ἀκτίνων ὁρώμενα μετεωρότερα φαίνεσθαι, τὰ δὲ ὑπὸ ταπεινοτέρων ταπεινότερα.
ϛ´. καὶ ὁμοίως τὰ μὲν ὑπὸ δεξιωτέρων ἀκτίνων ὁρώμενα δεξιώτερα φαίνεσθαι, τὰ δὲ ὑπὸ ἀριστερωτέρων ἀριστερώτερα.
ζ´. τὰ δὲ ὑπὸ πλειόνων γωνιῶν ὁρώμενα ἀκριβέστερον φαίνεσθαι.

1) Let it be established that visual rays move along straight lines from the eyes and produce some distance between one another;
2) and that the shape inscribed by the visual rays is a cone that has its vertex at the eye and its base at the limits of the things being seen;
3) and that those things are seen against which the visual rays fall, while those things are not seen against which the visual rays do not fall;
4) and that those things which are seen [subtended] by a greater angle appear larger, those things which are seen [subtended] by a smaller angle appear smaller, and those things which are seen [subtended] by equal angles appear equal;
5) and that those things which are seen by higher rays appear higher, while those which are seen by lower rays appear lower;
6) and likewise that those things which are seen by rays more to the right appear more to the right, while those things which are seen by rays more to the left appear more to the left;
7) and that those things which are seen [subtended] by greater angles appear more sharply ([Eucl.] *Opt. def.* 1-7, B).[439]

Although these statements may seem to be theory-neutral, a set of geometrical properties applicable to a number of physical accounts, they still construct vision as a process involving visual rays that extend from the eye and form a visual cone. No longer does sight concern images, *eidola* or objects, since only lengths and other geometrically

[439] Netz 1999: 89-103 mentions that these are not definitions, but second-order statements, since they do not provide foundational descriptions. We should also remember that it was modern editors who enumerated and formatted these statements; in the original text, the definitions would have been written as a single sentence, as the grammar indicates.

inscribed figures are allowed inside the diagrams.[440] Moreover, Euclid almost exclusively treats vision as though it were monocular—no doubt because it is easier to construct geometrical proofs with a single point rather than with two discrete sources of visual rays. He also fails to mention light and colour, let alone provide an explanation of either, and their omission implies that they are unnecessary to construct a science of vision.[441] That is, he reconstructs vision as a geometrical phenomenon and in so doing narrows its meaning, now excluding many of the aspects that were previously held to be some of its essential features.

Even within his geometrical framework of vision, however, Euclid has not completely left behind the material world. In fact, several definitions have direct physical implications. For example, definition 1 posits that visual rays [ὄψεις]: 1) project from the eyes; 2) have space in between them; and 3) move along straight lines.[442] Moreover, definition 3 indicates that we only see those points on which the visual rays fall, while proposition 1 extends this assertion to indicate that objects can actually lie in between the rays (fig. 12):

[440] For a similar observation, see G. Simon 1988: 70.

[441] Cf. M. Smith 1999: 30. Jones 1994: 56 makes the claim that "the conspicuous omission of any reference to colour, for example, means no more than that geometrical analysis seemed to have nothing to offer this aspect of the theory of appearances." We ought to remember that several theories of colour rely on the weakening of a visual ray over distance, which is a phenomenon that can be treated with a diagrammatic representation. Moreover, Aristotle uses diagrams to 'prove' his account of the rainbow's colour at *Mete.* 375b9-15. Thus, it is not the case that geometrical analysis *intrinsically* has nothing to offer explications of colour, simply that diagrams do not construct vision with this feature as an essential part of the phenomenon.

[442] Part of the reason modern commentators, such as Brownson 1981, were able to hold an interpretation of the *Optics* as an analytic exercise was that they use the A manuscript, which begins with the line "Let it be posited that *straight lines* leading from the eye are born with respect the distance of a great magnitude" [ὑποκείσθω τὰς ἀπὸ τοῦ ὄμματος ἐξαγομένας εὐθείας γραμμὰς φέρεσθαι διάστημα μεγεθῶν μεγάλων]. This formulation is more conducive to a strictly mathematical interpretation.

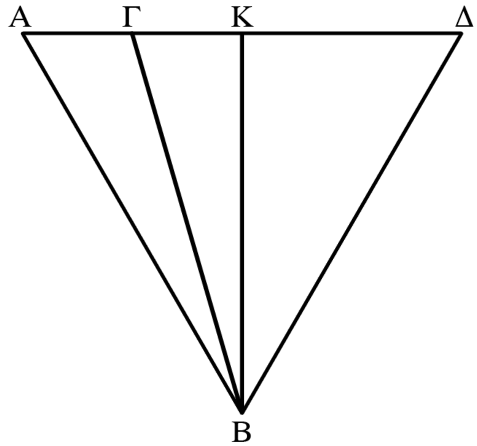

Fig. 12 [Eucl.] *Opt.* prop. 1, B

οὐδὲν τῶν ὁρωμένων ἅμα ὅλον ὁρᾶται.
ἔστω γὰρ ὁρώμενόν τι τὸ ΑΔ, ὄμμα δὲ ἔστω τὸ Β, ἀφ' οὗ προσπιπτέτωσαν ὄψεις αἱ ΒΑ, ΒΓ, ΒΚ, ΒΔ. οὐκοῦν ἐπεὶ ἐν διαστήματι φέρονται αἱ προσπίπτουσαι ὄψεις, οὐκ ἂν προσπίπτοιεν συνεχεῖς πρὸς τὸ ΑΔ. ὥστε γένοιτο ἂν καὶ κατὰ τὸ ΑΔ διαστήματα, πρὸς ἃ αἱ ὄψεις οὐ προσπεσοῦνται. οὐκ ἄρα ὀφθήσεται ἅμα ὅλον τὸ ΑΔ. δοκεῖ δὲ ὁρᾶσθαι ἅμα τῶν ὄψεων ταχὺ παραφερομένων.

Nothing of the things being seen is seen whole all at once.
For let ΑΔ be something being seen, and let Β be the eye from which the rays ΒΑ, ΒΓ, ΒΚ and ΒΔ extend. And so, since the extended rays are born at an interval, they would not fall continuously across ΑΔ. So that there are intervals along ΑΔ on which the visual rays will not fall. Therefore, ΑΔ will not be seen whole at the same time. It *seems* to be seen at the same time since the visual rays move quickly side to side ([Eucl.] *Opt.* prop. 1, B, emphasis mine).

According to this proposition, because visual rays are discrete (def. 1), we never see the entirety of an image all at once; rather, we only see those points onto which they fall (def. 3). To be sure, if actual visible objects can slip in between the visual rays—which can themselves "move quickly side to side"—the lines in the diagrams must stand in for actual physical entities and cannot be pure mathematical abstractions. The *Optics*' geometrical claims thus implicate themselves a certain set of physical assumptions.[443] But

[443] Cf. Berryman 1998: 186. Jones 1994 suggests that Euclid bears a great debt to Strato of Lampsacus, since Strato not only proposed a type of luminous ray theory, but he also denied there are 'continuous'

how do these implications relate to the geometrical tools with which Euclid articulates vision? Are his diagrams abstractions of some physical theory?

We have already discussed how previous thinkers construe the extramissionist substance as a single extension or unified stream flowing from the eye. In the very first definition, however, Euclid has switched this vocabulary into the plural, now referring to the visual *rays* [ὄψεις]. On the one hand, we could take this as merely an inconsequential change, nascent in earlier accounts. On the other hand, even a glance at a single proposition in the *Optics* can shed light on why this reformulation may have occurred. For instance, proposition 2 attempts to explain variations in visual acuity (fig. 13):

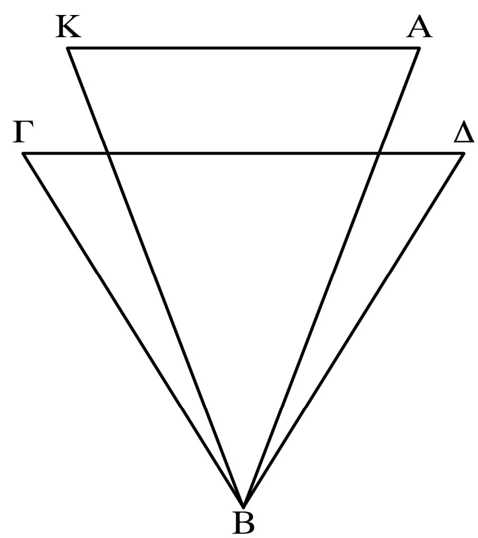

Fig. 13 [Eucl.] *Opt*. prop. 2, B

[συνεχές] areas of void; cf. Simplic. *In Arist. Phys.* 4.9 = 65a Wehrli. Strato also posits that tiny 'interstitial' pores exist in between the imperceptibly small bodies that compose the world (Strato, fr. 54-67 Wehrli; cf. Hero, *Pneum.* 1 = fr. 56 Wehrli. Jones argues that these interstitial pores are behind Euclid's ideas about the discrete visual rays. Berryman 1998: 196 also holds that Strato's theories are similar to Euclid's, although she ultimately maintains that the *Optics* is theory-neutral. Given that interstitial pores and the spaces between visual rays are slightly different concepts and the fact that Strato only mentions the ἀκτῖνες and αὐγαί of the sun and not of the eye (65a-b Wehrli), I am more hesitant than Jones to insist that his doctrines directly influenced the implicit physical hypotheses behind the *Optics*.

> τῶν ἴσων μεγεθῶν ἐν διαστήματι κειμένων τὰ ἔγγιον κείμενα ἀκριβέστερον ὁρᾶται.
> ἔστω ὄμμα μὲν τὸ Β, ὁρώμενον δὲ τὸ ΓΔ καὶ τὸ ΚΛ· χρὴ δὲ νοεῖν αὐτὰ ἴσα καὶ παράλληλα, ἔγγιον δὲ ἔστω τὸ ΓΔ· καὶ προσπιπτέτωσαν ὄψεις ὡς αἱ ΒΓ, ΒΔ, ΒΚ, ΒΛ. οὐ γὰρ ἂν εἴποιμεν, ὡς αἱ ἀπὸ τοῦ Β ὄμματος πρὸς τὸ ΚΛ προσπίπτουσαι ὄψεις [ὡς] διὰ τῶν Γ, Δ σημείων ἐλεύσονται. ἢ γὰρ ἂν τριγώνου τοῦ ΒΔΛΚΓΒ ἡ ΚΛ μείζων ἂν ἦν τῆς ΓΔ· ὑπόκειται δὲ καὶ ἴση. οὐκοῦν τὸ ΓΔ ὑπὸ πλειόνων ὄψεων ὁρᾶται ἤπερ τὸ ΚΛ. ἀκριβέστερον ἄρα φανήσεται τὸ ΓΔ τοῦ ΚΛ.
>
> Of equal-sized magnitudes lying at a distance, the ones lying nearer are seen more acutely.
> Let there be an eye, Β, and let ΓΔ and ΚΛ be the things being seen; it is necessary to understand that they are equal and parallel, but let ΓΔ be nearer. And let *visual rays* fall forward, as lines ΒΓ, ΒΔ, ΒΚ, ΒΛ. For we would not say that the *visual rays* extending from the eye Β to the object ΚΛ through the points Γ and Δ will comprehend it. For the line of triangle ΒΔΛΚΓΒ is larger than ΓΔ; but it is subtended by an equal angle. And so ΓΔ is seen by more visual rays than ΚΛ. Therefore, ΓΔ will appear more acutely than ΚΛ ([Eucl.] *Opt*. prop. 2, B).

Whereas Aristotle's geometry of the rainbow depicted only a single sightline, this proof requires multiple lines be drawn from the eye. Indeed, *all* Euclid's propositions require that at least two projections be extended from the viewer to one or more visible magnitudes. Thus, by adopting the diagram as a cognitive tool, Euclid reconfigures the mechanism of vision according to these new geometrical parameters. As such, a unified ὄψις becomes reconceptualized as multiple discrete lines extending from the eye, just as the geometry requires.

I should be careful not to overstate my claims. The idea of multiple visual streams was certainly available to thinkers without diagrams. Plato and the Pythagoreans *could* have proposed that more than one extension constituted the visual stream pouring from the eyes. Yet, without any argument, problem or visual heuristic requiring it, the idea was not expressed. To support the claim that geometrical practices in particular were instrumental in this conceptual switch, we can note that references to multiple visual rays emerge only in geometrical texts depicting sight in this multiform manner. Whereas Empedocles,[444] Plato,[445] Theophrastus[446] and Aristotle's *Meteorologica* (which only drew a single visual ray)[447] all refer to ὄψις in the singular, the *Problemata* (which also uses diagrams to represent the rectilinear propagation of sight, but does so with multiple rays) shifts from speaking of ὄψις in the singular and of ὄψεις of both eyes to speaking about ὄψεις in the plural.[448] To be sure, earlier texts refer to ὄψεις, but these instances denote eyes or "images" (especially those that transpire in dreams)[449]—not multiple visual rays. The diagrammatic representation of vision thus seems to have produced a conceptual shift, providing a material manifestation of a multi-ray theory of vision.[450]

While acknowledging the physical implications of these definitions, we should note that the lines in the diagrams bear striking resemblance to the hypothetical entities they supposedly represent. Indeed, although other models suggest that the visual

---

[444] Arist. *Sens.* 437b14; cf. Theophr. *De sens.* 7.15; 17.4; 19.4.

[445] Pl. *Tim.* 64d5-6; 67d2-4; 67e7-8; *Rep.* 507d11-12.

[446] Theophr. *De vert.* 402.13, 40, 49, 53.

[447] Arist. *Mete.* 370a19; 373a2-18; 373a35-b8; 377b7-10. At *Mete.* 343a3, Aristotle makes use of ὄψις in the singular with reference to Hippocrates of Chios, though it is unclear whether this is Hippocrates' language or Aristotle's.

[448] For references to the singular, see [Arist.] *Pr.* 3.10.872b4-14; 4.3.876b28; 11.58.905a35; for the ὄψεις of both eyes, see *Pr.* 31.7.957b41; 31.20.959b1; for multiple visual rays, see *Pr.* 3.10.872b13; 3.30.875b10; 15.6.911b21-23; 15.7.912a2. I am indebted to Berryman 1998: 184-185 for these observations.

[449] For the use of ὄψεις to describe the images in dreams, see Aesch. *Sept.* 710-711; *Vinc.* 645; Isocr. *Ev.* 21.4; Pl. *Rep*. 572a8; *Leg*. 887d6; 910a3. For the use of ὄψεις to describe eyes (or as a synecdoche for countenance), see Heracl. DK 22 B 26, ln. 2; Soph. *OT* 1328; *An*. 52; Xenoph. *Symp*. 1.9.3; 5.6.7; [Hippocr.] *Prog*. 2.27; 7.7; Theophr. *De sens*. 14.

[450] Archim. *Aren.* and [Eucl.] *Catop.* also provide examples of this, insofar as they use ὄψις in the singular whenever depicting a single visual ray, but use (perhaps not surprisingly) ὄψεις in the plural whenever depicting multiple lines of sight.

substance exiting the eye acts like a projectile or a stream,[451] Euclid's diagrams often presume that visual rays act as rigid straight lines. For example, although visual rays are said to be "born from" [φέρεσθαι] the viewer and "fall forward" [προσπίπτειν], which may both seem to imply some type of motion, in practice he often employs the visual rays in a different way. The *Optics* thus hedges on whether any forward trajectory takes place or not. For instance, proposition 1 quoted above demonstrates how the spaces in between the rays are filled, not by more rays flowing into those gaps, but by "rays moving side to side" [τῶν ὄψεων παραφερομένων].[452] In order for his proposition to be valid (which is, after all, a quasi-physical argument), he must consider the rays to be actual rigid physical lines protruding from the eyes, just like the rigid marks on the page. In other words, they cannot be streams flowing forward, as in Plato's explanation. Likewise, propositions 49-51 and 53-54, which all involve objects in motion, require a 'fan' of stable rays in order to function. One proof from this series will illustrate this sufficiently (fig. 14):

[451] For instance, [Arist.] *Pr.* 11.23.901b21-23 and 16.13.915b18-35 take sounds, light and projectiles as entities that all obey the law of reflection at equal angles; cf. Arist. *An. Post.* 98a27, which claims that echoes, mirrored reflections and rainbows are all part of the genus of reflection, though different in species. He does this without reference to a law of reflection; cf. Jones 1994: 74, n. 47; cf. n. 414.

[452] [Eucl.] *Opt.* prop. 1, B.

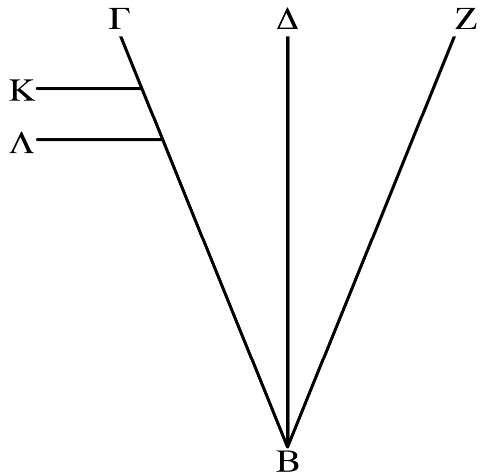

Fig. 14 [Eucl.] *Opt.* prop. 54, B

> τοῦ ὄμματος παραφερομένου τὰ πόρρω τῶν ὁρωμένων καταλείπεσθαι δόξει. ἔστω γὰρ ὄμμα τὸ Β, ἀφ' οὗ ἤχθωσαν ἀκτῖνες αἱ ΒΓ, ΒΔ, ΒΖ, ὁρώμενα δὲ τὰ Κ, Λ. οὐκοῦν τοῦ ὄμματος παραφερομένου πρὸς τοῖς Γ μέρεσι θᾶττον παρελεύσονται αἱ ὄψεις τὸ Κ ἤπερ τὸ Λ. Δόξει ἄρα τὸ Κ ὑπολείπεσθαι, τὸ δὲ Λ εἰς τοὐναντίον φέρεσθαι, τουτέστιν ὡς ἐπὶ τὰ πρὸς τῷ Ζ μέρη.
>
> When the eye moves sideways, visible objects that are further away will appear to be left behind. Let Β be the eye, and let the rays ΒΓ, ΒΔ and ΒΖ be led from it, and let Κ and Λ be the things being seen. And so when the eye moves sideways towards the areas around Γ, the visual rays will move past Κ faster than Λ Therefore Κ will appear to be left behind, but Λ will seem to move in the opposite direction, as though to the area on the Ζ ([Eucl.] *Opt.* prop. 54, B).[453]

In order for this proof to work, the rays actually have to maintain lateral motion, which indicates that they must be rigid bodies swinging sideways. If the rays were constantly streaming from the eyes, they would have none of the sideways momentum required by the proof and would instead continue their forward trajectory (think of water flowing from a hose being turned side to side). Euclid's rays therefore more closely resemble sticks than either streams or bullets—more precisely, they seem to derive some of their physical attributes from their geometric expression.

[453] Jones 1994: 54-55 has correctly pointed out that there is a mistake in the proof: the visual rays will move faster past Λ than Κ, since the distance between the rays that Λ travels will be shorter.

Similar physical model can be found in the Peripatetic tradition linked to these geometrical accounts of vision. For example, Theophrastus conceived of the visual ray as a rigid body extending from the pupil to an object, and his explanations of dizziness and vertigo rely on the fact that when this rigid ray is shaken or moved, the motion directly impacts the fluids in the eye.[454] Similarly, the pseudo-Aristotelian *Problemata* relies on extended, rigid rays to explain why drunks get the 'spins.'[455] It is hard to assert that the idea of a rigid visual extension derived only from geometrical diagrams. Nevertheless, calling the straight line an abstraction of some physical theory seems insufficient to describe the visual ray's relationship to its own geometric depiction. In any case, even if geometrical line did not create the idea of visual rigidity, the diagram provided a medium around which ideas about extramission could coalesce. In fact, throughout antiquity geometrical treatments of vision and visual ray theories were consistently grouped together, becoming almost synonymous. Calchidius names the Peripatetics and the "mathematicians" [μαθήματικοι] as those who hold a visual ray theory,[456] as do Porphyry[457] and Alexander of Aphrodisias.[458] Thus, although diagrams did not produce extramissionist theories, they provided a visual heuristic for their expression. The inherent conceptual sympathy between rays and the lines on the page was no doubt a large contributing factor.

---

[454] Theophr. *De vert.* 6-9; cf. [Arist.] *De color.* 791a19-27; 794a6-8, which seems to indicate that rays shove other media aside.

[455] [Arist.] *Pr.* 3.9.872a18-872b3; 3.20.874a5-20.

[456] Calchid. *In Tim.* 238, 279.

[457] DK 68 A 126a.

[458] Alex. Aphr. *In de sensu* 27.27-28.15.

At the same time, these geometrically inscribed rays seem to operate both in and out of the mathematical realm, while their physical features seem bound up with, if not actually derived directly from, their geometrical features. In other words, they operate with the hybrid ontology described above. One particular example will illustrate this more clearly. On the one hand, for Euclid's formulation to work the rays need to have width, since without any girth, each individual ray would only fall on a single geometrical point—which has no magnitude. In this case, no ray would comprehend any spatial area. As a consequence, no matter how many rays exited the eye and how much they moved back and forth, they would never combine to see anything. On the other hand, attributing some magnitude to the visual rays produces another set of problems. We need only think of a bundle of straws cinched together with an elastic band at their end. Regardless of how wide they spread, the surface area covered at the end of the straws can only ever equal the surface area that they cover at their starting points. Thus, at the very least, a surface area no greater than the pupil would need to spread across the entire visual field, up to and including the celestial bodies. That would require a tremendous amount of wiggling back and forth to cover the gaps. If we increase the surface areas of the rays to alleviate this problem, they simply would not fit into the eye. If the rays were wide enough to see the entire visual cone—even if it took some movement back and forth to fill in the gaps—this would present considerable compression problems when they reached the same point in the eye, as Euclid's geometry demands. In fact, it is impossible for them to have *any* material magnitude and all occupy the same physical location at the same time.[459] These visual rays therefore operate in two realms simultaneously: at the vertex of the visual cone, they function as abstract mathematical entities, overlapping

[459] Cf. section 5.2 below.

without spatial magnitude, but by the cone's base they have transformed into material, physical things with breadth and girth. The lines on the page activate different and mutually exclusive arguments both inside and outside the diagram.

4.3 The Visual Cone and Geometrical Astronomy

At this point, I have examined how the diagram provides a material heuristic with which to understand the visual ray. I now want to consider the shape that those rays collectively form—the visual cone posited in definition 2—to see how this idea also derives from geometrical, rather than physical assumptions. The concept of a visual cone remains unproblematized in scholarly accounts and has been taken to be somehow natural, something ostensibly meriting little interrogation—but let us consider our own experience of sight and perform a short experiment. Wiggle your fingers at arms length in front of your face. Then, while continuing to look forward, move them back gradually into your peripheral vision until they can no longer be seen. Doing so will reveal that our sightline reaches roughly 180° across our visual field (depending on the person). The area far surpasses any width that could reasonably be considered the base of cone extending from the vertex of the eye.[460] The actual field of vision moves so far back that it would more fittingly be considered a full hemisphere. How, then, did the assumption that vision falls in a conical shape become so natural as to barely be challenged, a feature assumed without argument? To what degree are geometrical technologies responsible for this notion?

[460] Eucl. *Elem.* 11, def. 18 shows that when Euclid uses the term, he may even mean a right-angled cone in particular, which would make the visual field even smaller.

At the very least, the idea of a visual cone belongs to at least *some* type of visual geometry, since it is, after all, a mathematically defined shape. More than that, however, the visual cone does not appear to have emerged prior to the rise of geometrical optics. Empedocles, the Pythagoreans and Plato all fail to mention it, despite their extramissionist, or hybrid-extramissionist theories. Instead, the first potential appearance seems to be in the *Meteorologica* passage discussed above, where Aristotle refers to the "lines" [γραμμαί] from the eye falling upon the hemisphere in a conical formation.[461] Even in this context, however, the cone stems from the particular geometry of the rainbow, and it is unclear whether Aristotle is proposing that the eye projects this shape naturally. Instead, *Optics* definition 2 above provides the first clear reference.[462]

Perhaps, though, the visual cone is simply an elegant and conceptually satisfying shape, and Euclid (and other geometrical authors) simply imported the idea *to* diagrams, rather than deriving it *from* any geometrical requirements. For instance, a cone seems to adequately describe the form of light streaming from a lamp (if the light source is equipped with a directional mechanism such as a wind screen) or pouring through a hole. Therefore, one could argue that the shape could have been adopted from one of these non-geometrical contexts. Yet, even considering the light streaming from a lamp as a cone interprets this optical technology according to a geometrical heuristic in its own right. More than this, however, it turns out that the conceptual connection with illumination is key to understanding the emergence of the visual cone as a cognitive

---

[461] Arist. *Mete.* 375b19-29.

[462] [Arist.] *Pr.* 3.9.872a18-872b3 mentions the visual cone as well (cf. 15.6.911b14-25), and this reference may predate the *Optics*, although it is hard to date this text and its *lemmata*. It is likely a contemporary, or slightly earlier reference than Euclid's. Since both present geometrical accounts of sight, it makes little difference to my argument which of the two came first. Theophr. *De vert.* 4.6-6.2 mentions a cone made by spinning the eyes around, but he does not talk about a visual cone projecting from the eyes.

tool—although the relevant illumination does not occur in the world of lamps and candles, but within the mathematical space of celestial geometry, where the source of rays is not a candle or the eye, but the sun.

The first potential reference to a *luminous* cone projecting from the sun comes from Anaximander, who describes the sun giving off rays, just like the spokes of a chariot wheel, which forms a shape like a trumpet.[463] Far more often, however, the idea appears in explanations of eclipses, which considers the cone of shadow cast by the earth.[464] Aristotle himself mentions that the sun projects just such a cone:

> …εἰ καθάπερ δείκνυται νῦν ἐν τοῖς περὶ ἀστρολογίαν θεωρήμασιν, τὸ τοῦ ἡλίου μέγεθος μεῖζόν ἐστιν ἢ τὸ τῆς γῆς καὶ τὸ διάστημα πολλαπλασίως μεῖζον τὸ τῶν ἄστρων πρὸς τὴν γῆν ἢ τὸ τοῦ ἡλίου, καθάπερ τὸ τοῦ ἡλίου πρὸς τὴν γῆν ἢ τὸ τῆς σελήνης, οὐκ ἂν πόρρω που τῆς γῆς ὁ κῶνος ὁ ἀπὸ τοῦ ἡλίου συμβάλλοι τὰς ἀκτῖνας, οὐδ' ἂν ἡ σκιὰ πρὸς τοῖς ἄστροις εἴη τῆς γῆς, ἡ καλουμένη νύξ· ἀλλ' ἀνάγκη πάντα τὸν ἥλιον τὰ ἄστρα περιορᾶν, καὶ μηδενὶ τὴν γῆν ἀντιφράττειν αὐτῶν.
>
> …if just as has now been demonstrated in the theorems concerning astronomy (namely, that the size of the sun is greater than that of the earth and that the distance of the stars to the earth is many time greater than that of the sun to the earth—just as that of the sun to the earth is greater than that of the moon to the earth), *the cone from the sun would not cast its rays* very far from the earth, nor would the shadow of the earth (which we call night) reach the stars; but *the sun would necessarily see all the stars around it*, and the earth would not block out any of them (Arist. *Mete.* 345b5-8, emphasis mine).

[463] Anaximan. DK 12 A 21, ln. 5.

[464] Herodot. 1.74 = DK 11 A 5 claims that Thales was the first to predict an eclipse, which could indicate that Thales drew a geometrical image of the cone of shadow cast by the sun; cf. Aristoph. *Aves* 992-1009. This seems unlikely to be the case, however, since Heath 1913: 12-23 has shown that Thales probably relied on the observational records of the Babylonians without any real causal picture of eclipses; cf. Dicks 1959; Burkert 1972: 413-417; Netz 2004: 246. According to doxographical reports, it was Anaxagoras who first demonstrated that a lunar eclipse is caused by the shadow of the earth (cf. Plut. *De fac. in orb. lun.* = DK 59 B 18; Plut. *Nic*. 23 = DK 59 A 18; 59 A 5; 59 A 42 (8); 59 A 76. At the same time, Anaxagoras is also purportedly the first to have included a diagram [συγγραφή] in his text (cf. Diog. Laert. 2.11 = DK 59 A 1; Clem. *Misc.* 1.78 = DK 59 A 36; Plut. *Nic*. 23 = DK 59 A 18). Democritus followed him in this (DK 67 A 1; cf. DK 68 A 89a), and the idea was then canonized within the tradition of geometrical astronomy; cf. [Eudox.] *Ars astr.* 18.16-25. For general accounts of early astronomy, see Heath 1913, 1932; Lloyd 1970: 80-98; 1973: 53-74; Pedersen 1974; Neugebauer 1975, v. 2: 573-776; Evans 1998; Graham 2013.

Although it is unclear to whose geometrical theorems Aristotle is here referring, and they could belong to any number of candidates dealing with the mechanism of eclipses, one possible candidate is Philip of Opus, who wrote a (now-lost) work entitled *On the size of the Sun, Moon and Earth*.[465] Although we lack Philip's own text, we can see a theorem fitting Aristotle's description in a similar treatise belonging to Aristarchus of Samos, *On the Sizes and Distances of the Sun and the Moon*. Aristarchus begins his text by establishing several hypotheses, including that the moon receives its light from the sun, which he then utilizes in the following proposition (fig. 15):

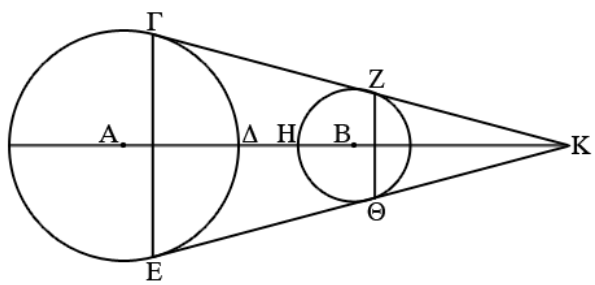

Fig. 15 Aristarchus, *De mag. sol. et lun.* prop. 2[466]

> ἐὰν σφαῖρα ὑπὸ μείζονος ἑαυτῆς σφαίρας φωτίζηται, μεῖζον ἡμισφαιρίου φωτισθήσεται. σφαῖρα γάρ, ἧς κέντρον τὸ Β, ὑπὸ μείζονος ἑαυτῆς σφαίρας φωτιζέσθω, ἧς κέντρον τὸ Α· λέγω ὅτι τὸ φωτιζόμενον μέρος τῆς σφαίρας, ἧς κέντρον τὸ Β, μεῖζόν ἐστιν ἡμισφαιρίου. ἐπεὶ γὰρ δύο ἀνίσους σφαίρας ὁ αὐτὸς κῶνος περιλαμβάνει τὴν κορυφὴν ἔχων πρὸς τῇ ἐλάσσονι σφαίρᾳ, ἔστω ὁ περιλαμβάνων τὰς σφαίρας κῶνος, καὶ ἐκβεβλήσθω διὰ τοῦ ἄξονος ἐπίπεδον· ποιήσει δὴ τομὰς ἐν μὲν ταῖς σφαίραις κύκλους, ἐν δὲ τῷ κώνῳ τρίγωνον. ποιείτω οὖν ἐν μὲν ταῖς σφαίραις κύκλους τοὺς ΓΔΕ, ΖΗΘ, ἐν δὲ τῷ κώνῳ τρίγωνον τὸ ΓΕΚ. φανερὸν δὴ ὅτι τὸ κατὰ τὴν ΖΗΘ περιφέρειαν τμῆμα τῆς σφαίρας, οὗ βάσις ἐστὶν ὁ περὶ διάμετρον τὴν ΖΘ κύκλος, φωτιζόμενον μέρος ἐστὶν ὑπὸ τοῦ τμήματος τοῦ κατὰ τὴν ΓΔΕ περιφέρειαν, οὗ βάσις ἐστὶν ὁ περὶ

[465] Suda IV, 733, 24-34 [Adeler].

[466] Diagram based on Heath 1913: 356, fig. 17.

> διάμετρον τὴν ΓΕ κύκλος, ὀρθὸς ὢν πρὸς τὴν ΑΒ εὐθεῖαν· καὶ γὰρ ἡ ΖΗΘ περιφέρεια φωτίζεται ὑπὸ τῆς ΓΔΕ περιφερείας· ἔσχαται γὰρ ἀκτῖνές εἰσιν αἱ ΓΖ, ΕΘ· καὶ ἔστιν ἐν τῷ ΖΗΘ τμήματι τὸ κέντρον τῆς σφαίρας τὸ Β· ὥστε τὸ φωτιζόμενον μέρος τῆς σφαίρας μεῖζόν ἐστιν ἡμισφαιρίου.
>
> If a sphere is illuminated by a sphere larger than itself, more than a hemisphere will be illuminated. For let a sphere, whose centre is B, be illuminated by a sphere larger than itself, whose centre is A. I say that the illuminated part of the sphere whose centre is B is larger than a hemisphere. For since the same cone (one having its apex on the side of the smaller sphere) inscribes two unequal spheres, let there be a cone inscribing the spheres; and let a plane be produced through their [common] axis. It will make (two) circles as cross sections inside the (two) spheres, and a triangle in the cone. Thus, make circles ΓΔΕ and ΖΗΘ in the spheres, and triangle ΓΕΚ in the cone. It is clear that the segment of the sphere along the arc ΖΗΘ, whose base is the circle with the diameter ΖΘ, is a part illuminated by the segment along the arc ΓΔΕ, whose base is the circle with the diameter ΓΕ, since it is orthogonal to the straight line AB. For the arc ΖΗΘ is illuminated by the arc ΓΔΕ. For the rays ΓΖ and ΕΘ are the most extreme. And the centre of the sphere in the segment ΖΗΘ is B; thus the illuminated part of the sphere is greater than a hemisphere (Aristarch. *De mag. sol. et lun.* prop. 2).

I have argued elsewhere that Euclid's *Optics* contains multiple propositions borrowed from the context of celestial illumination, and that propositions 23-27 in particular adopt some of the conclusions also portrayed in Aristarchus' proposition above.[467] We might also consider, then, the conceptual debt that optics owes to celestial geometry with respect to its key concepts. In fact, the very idea of a visual cone was likely adapted from the geometry of celestial illumination.

Several arguments support this claim. To begin with, the same authors who supposedly wrote the early optical treatises also wrote astronomical texts, including Philip of Opus and Euclid. Moreover, several linguistic details support the fact that the influence moved from astronomy to optics, rather than the other way around. For example, in definition 5, Euclid switches from talking about ὄψεις to talking about

[467] Webster 2014.

ἀκτῖνες, treating them as synonymous. Earlier authors, however, did not use these terms interchangeably (in part because thinking about vision in terms of multiple visual *rays* only emerged through a geometrical treatment of vision, as I have been arguing). Early uses of ἀκτῖνες construe them as weapons of the sun, projectiles or darts that Apollo hurls down from above,[468] or, more frequently, the sun's general light.[469] To be sure, many other instances expand on this usage, referring to the sun *seeing* the lands below by means of these rays,[470] but the active role that rays play in perception seem confined to this particular heavenly body. By way of metaphor, however, a few authors do refer to the 'rays' of the eye, describing the gleam that shines off of them,[471] but in these cases, there is little indication in these cases that the eyes actually see by means of these entities.[472] To give one striking example, Theophrastus does not include this vocabulary in any of the visual theories catalogued in *De sensu*. Treating the ἀκτῖνες as the operational mechanism of the eye does not seem to have appeared outside of geometrical optics until the diagram allowed ὄψεις and ἀκτῖνες to merge into a single concept. As a result, in the same generation as Euclid, Epicurus could now claim that we neither see

468 Cf. Hom. *Od.* 5.479; 19.441; Thales DK 11 A 21, ln. 5; Eur. *Phoen.* 5; *Ion* 1136; *Rhes.* 992; Timoth. *fr.* 24.2; Speusip. *fr.* 85, ln. 3.

469 Cf. Pind. *Olymp.* Ode 7, 70; Aesch. *Persae.* 364, 503; Anaxag. DK 59 A 80, ln. 4; 85, ln. 8; Eur. *Bac.* 679; *Alc.* 208.

470 Hom. *Od.* 11.16; *Hom. Hymn. In solem*, *In cerem* 70; Hes. *Theog.* 760; Pind. *Fr. Paian* 52k, ln. 1; Aesch. *Prom. Vinc.* 797; *Agamemn.* 676; Eur. *Med.* 1252.

471 Cf. Pind. *Frag.* 123, *Encom.* ln. 3; cf. Pind. *Isthmia*, Ode 3/4, ln. 60; Aristoph. *Vesp.* 1032; *Pax* 755.

472 Emped. DK 31 B 84, ln. 33, presents the sole borderline cases (cf. DK 31 A 90, ln. 1 = Aët. 4.13.4), insofar as he compares the eye to a lamp, which "shines across the threshold with tireless rays" [λάμπεσκεν κατὰ βηλὸν ἀτειρέσιν ἀκτίνεσσιν], but as was discussed in the previous chapter, Empedocles does not consider this the main mechanism of visual perception.

through rays [διὰ τῶν ἀκτίνων] nor streams from us [ῥευμάτων ἀφ' ἡμῶν],[473] while in the next generation after, Chrysippus could refer to the fiery rays from the eyes [ἐκ τῆς ὄψεως ἀκτῖνες πύριναι].[474]

More than simply showing the debt one field of applied mathematics owes to another, the adaptation of the cone from a celestial to an optical context demonstrates ancient optical authors' reliance on the diagram as a material tool with which to conceptualize vision, since in celestial illumination, the sun casts a cone of *shadow* with the interposition of the moon,[475] while optics transforms this shape into an area of visual *perception*. Despite the fact that these two shapes represent almost opposite physical circumstances (invisible/visible), their manifestation in a diagram is identical. Conical geometry makes no distinction between using ray-lines to denote the edge of illumination and the borders of a visual cone. As a result, using the diagram to conceptualize vision allowed optical theorists to repurpose the earth's conical shadow as a useful way to formulate sight.

Scholars have long proposed that extramission theories arose because of a conceptual conflation between the eye and the sun. While this is true, the 'sun' in this context must be understood as an entity formulated within a particular set of geometrical parameters. Rather than moving directly from physical ideas about solar illumination directly to physical ideas about the eye, the diagram provided the site where both processes were conceptualized and conflated. As a result, once vision was translated into

[473] Epic. *Epist. ad Her.* 49.4.

[474] *SVF,* fr. 866, ln 6.

[475] The close association between celestial illumination and geometrical astronomy seems to have been well-known, since at Aristoph. *Aves* 1009, Meton mentions that he'll draw a diagram, with a compass, claiming "just as from a star, itself being round, rays will beam out rays in every direction" [ὥσπερ δ' ἀστέρος αὐτοῦ κυκλοτεροῦς ὄντος ὀρθαὶ πανταχῇ ἀκτῖνες ἀπολάμπωσιν].

this diagrammatic space, the geometrical usefulness of the visual cone changed into a natural assumption, taken for granted without argument even by theorists outside of the geometrical tradition. That is, authors and commentators, both ancient and modern alike, conceptualized their own visual experience through the geometrical heuristic of a visual cone.

4.4 Euclid's *Optics* and Constructing Appearances

If the application of diagrams constructs vision around a geometrically useful shape, we can also ask how Euclid's geometry affects his account of visual appearances more broadly. That is, if his operational definition of sight no longer includes colours or images and instead focuses on the appearance of magnitudes and shapes, how do geometrical practices relate to the appearances they ostensibly elucidate? This becomes especially important to examine, since there is common conception among scholars that the *Optics* was written in order to explain and systematize subjective appearances and error formation, perhaps even as a response to a growing skeptical tradition.[476] For these scholars, proposition 9, "why does a square appear round when seen from a distance?" provides the exemplary case.[477]

[476] Panofsky 1991: 66; Andersen 1987; G. Simon 1988; Jones 1994: 47; Berryman 1998. This idea appears as early as Gemin. *Frag. Opt.* 22, who lists the apparent convergence of columns, the rounding of towers and unequal things appearing equal as phenomena that optics explains; cf. Procl. *In Eucl. Elem.* 40, who claims that the very subject of optics is the illusions created by objects at a distance, citing the convergence of parallel lines and the round tower as examples. Pl. *Rep.* 602c9-d5 presents different examples of the paradigmatic optical illusions, namely, straight things appearing bent in water, things of the same magnitude appearing different sizes at various distances (cf. *Rep.* 523c1-6) and painting with shadows to make flat surfaces appear concave or convex [σκιαγραφία]. Only one of these so-called illusions is dealt with in the *Optics*.

[477] Berryman 1998: 180-186 treats the rounded square as a general problem of resolution applicable to every object. Moreover, she gives this particular proposition considerable weight, suggesting not only that it shows the motivation behind the *Optics* as a whole, but also that the Euclidian author's success in explaining this problem led to his theory supplanting Aristotle's in the Peripatetic tradition. To my mind,

The square tower appearing round is well known from Lucretius' *De rerum natura*, where he argues that intervening air atoms strike against the *simulacrum* as it floats from the visible object towards the viewer, thus dulling the edges of the image.[478] The problem appears in essentially the same form in Sextus Empiricus, Plutarch, Diogenes Laertius and Tertullian,[479] and it is institutionalized in the optical tradition, appearing in both the pseudo-Aristotelian *Problemata* and Ptolemy's *Optics*, while Geminus and Proclus cite it as one of the paradigmatic optical illusions.[480]

Euclid's answer is slightly different from the Atomists. As opposed to suggesting that the rays degrade at all, he relies on his earlier assertion in proposition 3 that "all visible things have some distance, upon reaching which they are no longer seen" [ἕκαστον τῶν ὁρωμένων ἔχει τι μῆκος ἀποστήματος, οὗ γενόμενον οὐκέτι ὁρᾶται]. His proof constitutes little more than drawing a square and restating this information (fig. 16):

this grants too much significance to a single geometrical argument—especially since it is not an especially successful one and does not reappear.

478 Lucr. *DRN* 4.353-363.

479 Sex. Emp. *Ad math*. 7.208.7-210.1; cf. Plut. *Adv.Col.* 1121a5-6; Diog. Laert. 9.85.8; Tertullian, *In de An.* 17; *In Eucl. Elem. proleg*. 1.13; 1.40. This is not to claim that Euclid was the problem's author. Epicurus is a contemporary to Euclid and perhaps the source; cf. Diog. Laert. 10.34. The idea may even have been around as early as Democritus, since Philoponus, *In gen. cor.* 23.1-16 mentions it while discussing Democritus' views, although Philoponus does not specifically attribute this doctrine to him and instead includes it in a list of generic misperceptions, including the dove's neck changing colour, the difference between Z and N and the circle appearing flat when seen from a low enough angle; cf. [Eucl.] *Opt.* prop. 22, B; cf. Arist. *GC* 315b9.

480 Ptol. *Opt.* 2.97; [Arist.] *Pr.* 15.6.911b19-21; Gemin. *Frag. opt.* 22; Procl. *In Eucl. Elem.* 40; cf. n. 476 above.

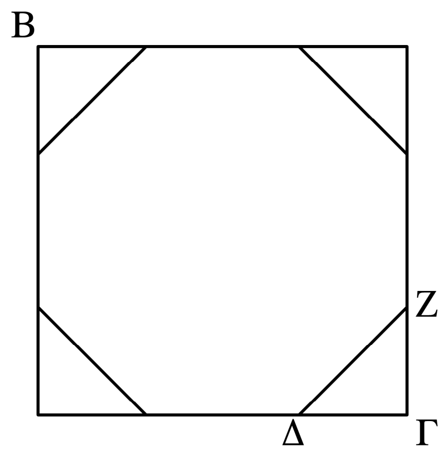

Fig. 16 [Eucl.] *Opt.* prop. 9, B

> τὰ ὀρθογώνια μεγέθη ἐξ ἀποστήματος ὁρώμενα περιφερῆ φαίνεται. ἔστω γὰρ ὀρθογώνιον τὸ ΒΓ [ἑστὼς μετέωρον] ἐξ ἀποστήματος ὁρώμενον. οὐκοῦν ἐπεὶ ἕκαστον τῶν ὁρωμένων ἔχει τι μῆκος ἀποστήματος, οὗ γενόμενον οὐκέτι ὁρᾶται, ἡ μὲν Γ ἄρα γωνία οὐχ ὁρᾶται, τὰ δὲ Δ, Ζ σημεῖα μόνον φαίνεται. ὁμοίως καὶ ἐφ’ ἑκάστης τῶν λοιπῶν γωνιῶν τοῦτο συμβήσεται. ὥστε ὅλον περιφερὲς φανήσεται.
>
> Rectangular magnitudes being seen from a distance appear round. For let ΒΓ be the square being seen from a distance. And so since all visible things have some distance, upon reaching which they are no longer seen, therefore, the corner angle Γ is not seen, but only the points Δ and Ζ. Likewise this will also occur at each of the remaining corners. The result is that an entire circle will be apparent ([Eucl.] *Opt*. prop. 9, B).

Euclid is arguing that at a certain distance the corners of the square will be small enough to fall into the gap between the rays, although the centre of the square will not, and thus a rounded, rather than a square object will appear. We might still ask, however, what, if anything does the diagram prove? The answer is, of course, not much. The image does not really supply a mathematical proof; it shows a square with its corners cut off. No visual rays are even presented—let alone their relative lengths—and the eye is left out entirely. As such, the proof cannot really address what it claims to demonstrate. So why draw this picture?

If Euclid were interested solely in explaining appearances, his physical theory would suffice; if he were interested solely in precisely geometrical proofs, this proposition would be inadmissible. Thus, his concern must be to inscribe visual experiences within mathematical space. He therefore draws a diagram that operates as a metonym for the phenomenon, both demonstrating it and explaining it away at the same time. The metonymic transfer becomes more apparent when we realize that the illusion of the rounded-square does not happen for modern eyes (at least in any unproblematic sense).[481] To us, square objects do not generally appear rounded from a distance.[482] Rather, the best attempt to make sense of such a statement is to say that the visible definition of square figures degrades over long distances,[483] with the result that it is impossible to determine accurately whether the figure is square or not. This, however, is not the same as saying it appears rounded. Consequently, this diagram is not truly explaining an appearance as much as *constructing* an appearance. Euclid is inscribing problems within a diagrammatic context and in the process simultaneously formalizing—both proving and visual demonstrating—the appearance he is attempting to elucidate.

Two other instances demonstrate something similar—notably, in propositions that at first seem to engage more earnestly with vision as it takes place in the world. The first

[481] Harry 1970: 61 makes a similar observation, giving a few possible examples of atmospheric conditions that could at best be said to blunt the corners, including mist and the shimmer of hot air. She ends up attributing this phenomenon, as well as a few other well-known observations to Epicurus' undocumented case of myopia. This seems unconvincing.

[482] In fact, an unknown editor has added 'standing from above' [ἑστὼς μετέωρον] in an attempt to make sense of this, presumably considering the proposition through the rounded *tower* example. My assumption is that this editor is imagining a cubical tower being viewed from above, which will appear slightly less square because of the perspective involved with three-dimensional figure (see Berryman 1998 for a similar account). This is not, however, what Euclid's proof suggests. Heiberg notes that the words have been added, although they also appear in prop. 9, A as well.

[483] Berryman 1998: 183, n.13 notes that her students tested whether this actually happened and they were unable to tell whether the tower was square or round, although it is unclear whether by "round" they mean cylindrical.

group (prop. 25-27) incorporates binocular vision into an account of the visibility of spheres, while the second (prop. 34-37) culminates in a demonstration of why a chariot wheel sometimes looks circular [κυκλοειδεῖς], and sometimes looks 'squished' [παρεσπασμένοι]. Let us deal with this second group first.

The foreshortening of chariot wheels is a false appearance known outside of the geometrical tradition, and multiple ancient images depict this phenomenon.[484] The *Optics* provide an account of this appearance, starting with proposition 34, which demonstrates that when the eye rests directly above a circle's centre, orthogonal to its plane, "all the diameters of the circle appear equal" [ἴσαι αἱ διάμετροι τοῦ κύκλου φαίνεται].[485] Euclid takes "all diameters appear equal" as equivalent to "all diameters appear circular," since the first formulation aligns closely with the definition of a circle in the *Elements*.[486] Proposition 36 employs this same equivalency, arguing that if we view a circle from an oblique angle, the diameters will not appear equal—and thus the circle will not appear circular. In both these instances, Euclid's conclusions are true, even if his definitions are not. Proposition 35, however, deals with a special case. In it, Euclid argues that when the eye rests obliquely to the plane of the circle, but at a distance precisely equal to its radius, the circle will once again appear perfectly circular (fig. 17):

[484] See White 1956; Knorr 1992.

[485] [Eucl.] *Opt.* prop. 34, B.

[486] Eucl. *Elem.* def. 1.15 describes the circle as "a plane figure contained by a single line such that there is a single point inside the figure from which all straight lines falling upon that line are equal to one another."

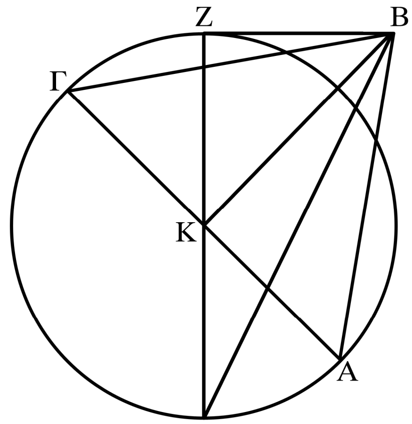

Fig. 17 [Eucl.] *Opt.* prop. 35, B

> καὶ ἐὰν ἡ ὑπὸ τοῦ κέντρου ἀναχθεῖσα μὴ πρὸς ὀρθὰς ᾖ τῷ ἐπιπέδῳ, ἴση δὲ τῇ ἐκ τοῦ κέντρου, ἴσαι αἱ διάμετροι φανήσονται.
> ἔστω κύκλος, οὗ κέντρον τὸ Κ, καὶ ἀπὸ τοῦ Κ μὴ πρὸς ὀρθὰς ἀνήχθω τῷ ἐπιπέδῳ ἡ ΚΒ, ἴση δὲ ἔστω τῇ ἐκ τοῦ κέντρου τοῦ κύκλου, καὶ ἐπεζεύχθωσαν ἀπὸ τοῦ Β σημείου αἱ αὐταὶ ταῖς πρότερον. οὐκοῦν ἐπεὶ ἴσαι ἀλλήλαις εἰσὶν αἱ ΔΚ, ΚΒ, ΚΖ, ὀρθὴ ἂν εἴη ἡ περιεχομένη γωνία ὑπὸ τῶν ΖΒΔ. διὰ τὰ αὐτὰ δὴ καὶ ἡ ὑπὸ ΑΒΓ ὀρθὴ ἂν εἴη· ἴσαι ἄρα ἔσονται ἀλλήλαις. τὰ δέ γε ὑπὸ ἴσων γωνιῶν ὁρώμενα ἴσα φαίνεται. ἴση ἄρα ἡ ΔΖ τῇ ΑΓ φαίνεται.
>
> And if the ray extended from the centre is not orthogonal to the plane of the circle, but it is equal to the radius of the circle, the diameters will appear equal.
> Let there be a circle, whose centre is K, and from the K let KB be erected, but not at a right angle to the plane of the circle; and let it be equal to the radius of the circle; and let the same rays be joined from B (to the points of the diameter) as in the previous proof. And so since ΔK, KB and KZ are all equal to one another, the angle ZBΔ would be a right angle. On account of these same reasons, angle ABΓ would be a right angle too. Therefore, they will appear equal to one another. And the things being seen by equal angles appear equal. Therefore, [diameter] ΔZ appears equal to [diameter] AΓ ([Eucl.] *Opt.* prop. 35, B).

As Knorr has shown, Euclid is correct in asserting that all the diameters will be subtended by right angles, but he fails to note that once the eye no longer occupies the apex of the hemisphere, the diameters will no longer appear to be diameters. Instead, as the eye progresses toward the edge of the circle, the diameters will also appear close to the edge. In short, circles viewed obliquely, even from a distance equal to radius, do *not* look circular. Proposition 35 is false. This so-called appearance is a phantom of its own diagrammatic explanation.[487] Euclid would know this if he looked at a wagon wheel under the circumstances he describes, but instead, by using the diagram as the proper space for vision, his constructs an appearance that no longer bears a direct relationship to vision in the world.

A second such example occurs within propositions 23-27, which concern viewing a sphere from various distances. Just as the previous group, these too seem to address the physical aspects of vision more directly, insofar as they incorporate binocular vision and are the only theorems in the *Optics* to do so. I have mentioned above that this set of proofs has been repurposed from the context of celestial illumination,[488] and a crucial detail supports this, namely that propositions 25-27 *would* function if they were about the round sun casting its rays on the moon, but do not function for two point-like eyes casting their rays on a sphere. The flaw is easiest to see in proposition 25 (fig. 18):

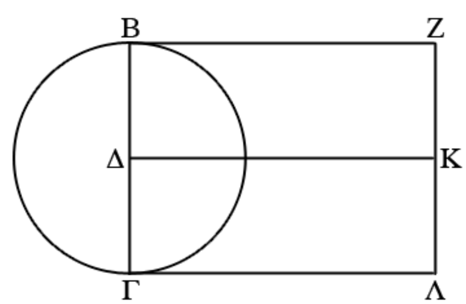

Fig. 18 [Eucl.] *Opt.* prop. 25, B

[487] Knorr 1992. Knorr also demonstrates that even circles viewed obliquely do not appear as true ellipses as Euclid claims; cf. [Eucl.] *Opt.* prop. 37, B.

[488] Webster 2014. More specifically, this series of propositions relates to Aristarchus' proofs about the illumination of celestial bodies that I have discussed above; cf. Aristarch. *De mag. sol. et lun.* prop. 1-3.

σφαίρας διὰ τῶν δύο ὀμμάτων ὁρωμένης, ἐὰν ἡ διάμετρος τῆς σφαίρας ἴση ᾖ τῇ εὐθείᾳ τῇ διεστώσῃ ἀπὸ τῶν ὀμμάτων, ἡμισφαίρον αὐτῆς ὀφθήσεται.
ἔστω γὰρ σφαῖρα, ἧς διάμετρος ἡ ΒΓ, καὶ ἀπὸ τῶν Β, Γ ἤχθωσαν πρὸς ὀρθὰς αἱ ΒΖ, ΓΛ, καὶ ἀπὸ τοῦ Ζ ἤχθω παρὰ τὴν ΒΓ ἡ ΖΛ, καὶ κείσθω ἓν ὄμμα ἐπὶ τοῦ Ζ, τὸ δὲ ἕτερον ἐπὶ τοῦ Λ, ἀπὸ δὲ τοῦ Δ κέντρου ἤχθω παρὰ τὴν ΒΖ ἡ ΔΚ. οὐκοῦν ἐὰν μενούσης τῆς ΔΚ τὸ ΒΚ παραλλελόγραμμον περιενεχθὲν εἰς τὸ αὐτὸ πάλιν ἀποκατασταθῇ, ὅθεν ἤρξατο φέρεσθαι, τὸ περιγραφὲν ὑπὸ τῆς ΒΔ σχῆμα κύκλος ἔσται, ὅς γε διὰ τοῦ κέντρου ἐστὶ τῆς σφαίρας. ὥστε τὸ ἡμισφαίριον τῆς σφαίρας μόνον ὀφθήσεται ὑπὸ τῶν Ζ, Λ ὀμμάτων.

When a sphere is seen by two eyes, if the diameter of the sphere is equal to the straight distance that stands between the eyes, half of the sphere will be seen.
For let there be a sphere whose diameter is the line ΒΓ; and from the points Β and Γ let lines ΒΖ and ΓΛ be extended at right angles; and from point Ζ let a line ΖΛ be extended parallel to ΒΓ; and let one eye be placed at Ζ and the other at Λ; and from the centre, Δ, let a line ΔΚ be extended parallel to ΒΖ. And so if, while ΔΚ remains stationary, the rectangle ΒΚ is rotated and returns again to the same spot whence it began to be moved, the shape circumscribed by ΒΔ will be a circle, which runs through the centre of the sphere. Thus, only half of the sphere will be seen by the eyes Ζ and Λ ([Eucl.] *Opt.* prop. 25, B).

The proof is relatively simple, but there is a substantial flaw in Euclid's reasoning; it has to do with translating a three-dimensional vision into a two-dimensional proof. Although Euclid correctly demonstrates that two eyes can potentially comprehend an entire *semicircle*, in order to prove the same thing about a *hemisphere*, he simply "rotates" the proof around the centre access Β. This rotation is crucial to the proof, but there is a major problem: it cannot possibly work for vision. Although it is perfectly acceptable to "rotate" the proof geometrically, we cannot rotate our eyes in the same way. In the world outside of the diagram, the eyes Ζ and Λ are fixed at two points in our head. Therefore, although we are able to see the full diameter of a hemisphere, the two spots at either pole are *always* invisible to our eyes (see fig. 19 and 20). We can see this more clearly by breaking the proof into two and examining the visual cone of each individual eye before joining them together.[489]

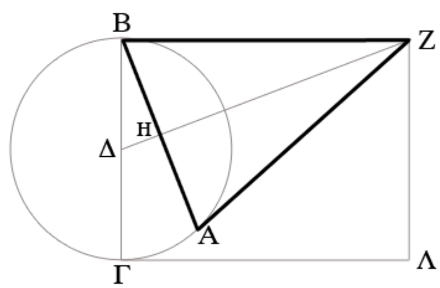

Fig. 19 [Eucl.] *Opt.* prop. 35, reconstructed step one

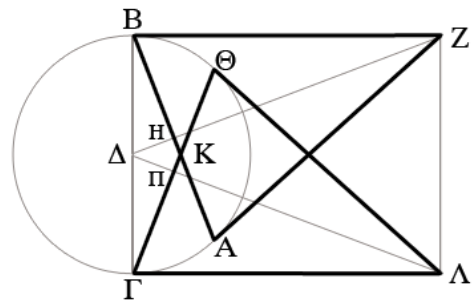

Fig. 20 [Eucl.] *Opt.* prop. 35, reconstructed step two

Euclid's proof is both incorrect and fails to accommodate the actualities of vision in the world. Geometry has allowed Euclid one set of practices, which have taken a type of epistemological dominance over the phenomenon that they are supposed to describe. In other words, the proper space of vision has become the diagram, and the physical theory to which Euclid ascribes is mediated by the set of mathematical practices that govern such a space.

Let us return, now, to the very first proposition of the *Optics* to ask: what is the status of the appearances that Euclid seeks to explain and how are they related to the geometrical proofs that supposedly explain them? Proposition 1 demonstrates that "Nothing of the things being seen is seen whole all at once." What the diagram predicts—ostensibly even 'proves'—is that we ought to see a 'pointillist' version of each object around us. Of course, Euclid explains this pointillism away by arguing that everything only *seems* to look whole because the visual rays projected from our eyes move quickly back and forth to cover the gaps. Thus, the diagram explains something that is an

[489] For a geometrical account of the revised proof, see Webster 2014.

appearance in no ordinary sense. Rather, this pointillist view of the world is only something that Euclid's own definitions and diagrams predict. It is an appearance that only appears inside the diagram. Euclid's diagrams thus do not necessarily explain phenomena, as much as they *construct* the phenomena. In doing so, they take epistemological precedence over the world they seek to explain. His text thereby constructs an implicit argument: even if it appears to you that you are viewing an object in its entirety, this is merely an illusion; it is the space of the two-dimensional diagram where vision correctly takes place.

4.5 Conclusion

In this chapter, I have expanded my definition of technology beyond the limits of what is considered under the heading of τέχνη in order to demonstrate how other sets of material practices can also shape physical theories. I have argued that although they do not operate as strict analogies, diagrams too operate by a type of comparison, possessing epistemological weight, insofar as they model the world outside their borders. As such, I argued that, like technological analogies, diagrams too construct a physical heuristic, albeit one visibly instantiated on the page. At the same time, I have shown that the way geometrical images model the world is far from straightforward, since the physical entities represented in mathematical proofs do not truly exist apart from their geometrical articulation. The physical qualities that theorists ascribe to these entities are bound up with their function within diagrammatic space. Therefore, far from being theory-neutral, diagrams actually facilitate and embody certain physical ideas. In turn, this establishes a new type of hybrid ontology, whereby entities activate arguments simultaneously inside and outside the parameters of the diagram. While the abstract aspects of geometry help articulate angles and spatial relations, the material, visible aspects of geometry produce assumptions about the visual ray, the visual cone and false appearances. In sum, just as with the metonymic use of technologies to explain natural phenomena, diagrams can operate as functional physical theories in their own right. They are material technologies through which theorists conceptualize the world.

CHAPTER FIVE
VISUAL AND GEOMETRICAL APPARATUSES

5.0 Introduction: Experimental and Cognitive Tools

Whereas modern science privileges experimentation as one of its primary and most powerful tools in the production of knowledge, ancient science relies more heavily on analogies when explaining and constructing theories, employing comparisons to provide support and verify claims. Over the course of the previous chapters, we have seen the implications of this methodology, as analogical heuristics become active in conceptualizing (and thereby predicating) how entities operate in the world. In this way, a technological environment becomes incorporated into accepted physical assumptions, not simply as a collection of principles, but as a set of cognitive tools. Yet, ancient natural philosophers and physicians did not neglect experiments entirely, and some scientific thinkers did attempt to intervene into nature, control variables and isolate causes. Although this experimentalism never became a general scientific program and we should not conflate ancient epistemological views with our own, we can still examine the technological apparatuses that were constructed as part of scientific experiments to ask how these devices affect explanations of natural phenomena. How do the ancients' scientific theories relate to technology when their science most resembles our own? Do experimental devices also form conceptual heuristics? How does the material construction of an apparatus influence how experimenters conceptualize the objects under investigation? In other words, how does this type of technology relate to theory in antiquity?

I do not intend to provide a broad account of experimentation in ancient science. Instead, I will focus on two authors, Ptolemy and Galen, who both utilize material implements to interrogate the behaviour of light and sight. That being said, geometry still features highly in their accounts; Ptolemy belongs squarely within the tradition of geometrical optics, and Galen borrows from this field to conduct his anatomical investigations. Moreover, the specific implements that I will discuss are geometrical in construction, functioning as material expressions of optical principles. In fact, it is often hard to discern when these writers are referencing diagrams that depict these devices and when they are discussing the devices themselves. The fluidity of these conceptual boundaries allows conclusions to be drawn simultaneously across multiple ontological realms. Moreover, the experience of vision becomes ever more structured by these experimental tools. As a result, both Ptolemy and Galen produce models of the eye that resemble their own apparatuses, as their investigative tools are incorporated into their hypothesized mechanisms of sight. Thus, in the first portion of this chapter, I will examine how Ptolemy's geometrical and experimental technologies infiltrate both his physical model of spatial perception and his physiological account of the eye, while in the second, I will illustrate how Galen turns the real and visible anatomy of the ocular nerves into perfect geometrical lines.

5.1 Ptolemy's *Optics*

After Euclid, the largest contribution to geometrical optics in antiquity came from Claudius Ptolemy (c. 100 AD—c. 178 AD), a Greek-speaking Roman, who, like Euclid before him, lived and worked in Alexandria. He was an active mathematician, geographer, astronomer and astrologer during the second century CE up to the time of Marcus Aurelius.[490] He wrote many works, but his most famous remains the *Suntaxis Mathematica*, widely known by the Arabic permutation of its title, the *Almagest*.[491] In this work, Ptolemy presents a systematic compendium of all astronomical knowledge using his characteristic "eclectic" or "syncretic"[492] methodology—that is, Ptolemy addresses and adopts various philosophical arguments, collects countless geometrical proofs and accommodates a wide range of astronomical evidence, all while he contributes his own considerable insights. In many ways, his *Optics*[493] fits this same mold. It includes discussions that both engage with and draw from the philosophical arguments of Plato, Aristotle and the Stoics, even as he explores the geometry of vision and catoptrics put forth by Euclid, Archimedes, Hero and others.[494]

At a basic level, the treatise is broken up into five books. Unfortunately, the first of these has been lost in the course of the text's problematic transmission, which has left us only with a Latin translation of an earlier Arabic version of the text.[495] Nevertheless,

---

[490] For Ptolemy's biographical details, see Boll 1894; cf. van der Waerden 1959; Toomer 1976: 186-206, 1984: 1-4; Taub 1993: 7-9; M. Smith 1996: 1-5.

[491] *Almagest* seems to have arisen from adding the Arabic article 'al-' to μέγιστος, which was a title later attached to the work; cf. Toomer 1984: 2.

[492] Neugebauer 1975, v. 2: 940 describes Ptolemy's philosophical affiliations as characterized by a "certain eclectic attitude." Taub 1993: 13 suggests the term "syncretic" as a replacement, since Neugebauer's use of eclectic carries unnecessarily pejorative overtones. Like most thinkers of his time, Ptolemy was not beholden to a single philosophical school, but incorporated arguments from multiple perspectives.

[493] M. Smith 1996: 2-3 argues that the *Optics* was one of Ptolemy's last works, written somewhere between 160 and 170 CE. LeJeune 1989: 26 asserts somewhat more cautiously that it was written somewhere in the third quarter of the second century CE.

[494] For Ptolemy's possible source texts, see M. Smith 1996: 14-17.

[495] Ptolemy's original Greek text has been lost, and instead, only the 12th century Latin translation of Eugene of Sicily remains (for biographical information about Eugene, whose life is quite well documented, see Haskins 1924: 155-193; Jamison 1957, LeJeune 1989: 9-13). Eugene's edition is itself only a translation of one of two earlier Arabic versions of the text (cf. Eugene, Ptol. *Opt.* 2, *proem*; cf. LeJeune

Ptolemy begins the second book by recounting what he established in the first, namely 1) how light and sight interact; and 2) how these two elements differ in their powers and characteristics [*virtutes et motus*].[496] Thus, the first book would have likely dealt with the more physical components of vision[497]—especially since the second book of the *Optics* addresses what could be called the metaphysical aspects of vision, enumerating all of the visible properties and characteristics, before moving on to binocular perspective and the geometrical mechanics of distance perception. Book three and four deal with reflection in plane, convex and concave mirrors, while book five investigates refraction and provides

---

1989: 28), and while he claims that this Arabic version translated Ptolemy's Greek directly, M. Smith 1996: 7, n. 21 argues that we do not know on which grounds Eugene makes this claim, and therefore it remains unknown whether another, Syriac intermediary existed; cf. LeJeune 1957: 15-18 for arguments in favour of a direct link between the Arabic text and a Greek original based on linguistic cues.

Govi 1885 produced the first modern edition of Eugene's translation, which made the *Optics* accessible to a wider public—although, as an optical scientist lacking philological training, he simply assumed that the oldest manuscript was the most accurate. LeJeune's 1956 critical edition corrected many of Govi's errors, and in 1989 he added an accompanying French translation to the second edition of his text. LeJeune's work, along with M. Smith's 1996 English translation have made the text accessible to an even wider audience. For a full textual history, see LeJeune 1948: 5-12; 1989: 26-139; M. Smith 1996: 5-14.

Because of the shaky transmission of the *Optics*, doubts were raised as to its authenticity, but scholars have almost all accepted the work as genuine, especially since there are three references to Ptolemy's Greek text in mid- to late-antiquity. Two are from the fourth and sixth centuries CE (Damianus, *De Opt.* 3 and Simplic. *In Arist. de caelo* 20), while one is from the eleventh (Simeon Seth, *Conspectus rerum naturalium* 24 Delatte). Olympiod. *In meteor.* 242 also mentions that Ptolemy considered the rainbow to have seven colours, an argument that does not appear in the extant text of the *Optics*, but may have originally been included in the now-lost first sections; cf. LeJeune 1989: 13-14, 271; M. Smith 1996: 6, 49-50. For arguments in favour of the text's authenticity, see Martin 1871, LeJeune 1956: 13-26, 1957: 13-25, 1989: 13-26. In recent years, only Knorr 1985: 27-105 has argued against Ptolemy's authorship, but LeJeune 1989: 133-138 provides a sufficient rebuttal; cf. M. Smith 1996: 13.

[496] Ptol. *Opt.* 2.1.

[497] LeJeune 1948: 15-17 argues that from Ptolemy's own description, it seems that the first book examined the physical aspects of vision, while the remaining four books examine the "subjective" and "psychological" aspects of vision. I take issue with his latter characterization, since at *Opt.* 2.104 Ptolemy describes reflection and refraction as illusions that arise in the passions of the visual flux, and thus sit in contrast to the "subjective" aspects of vision dealt with at *Opt.* 2.103 and 2.134-141. In contrast to LeJeune's assessment, M. Smith 1996: 20 simply suggests that the first book would have examined "optics proper," including "the basic geometry of visual radiation," but this, at least in part, is also dealt with in the second book from *Opt.* 2.52-73. In these sections, Ptolemy explains how we perceive size, shape, magnitude and location—all aspects of the basic geometry of vision. Therefore, I see no reason why we should assume Ptolemy would have also explained these aspects in the first book, especially when he makes no mention of this in his summary.

an experimental articulation of the refractive indices of glass, water and air. Put simply, then, book one and two examine light, sight and perspective; book three and four deal with reflection; and book five investigates refraction.[498]

In many respects, Ptolemy participates squarely within the tradition of geometrical optics. All five extant books of the *Optics* include diagrams as integral parts of their explanations, and geometry takes up the majority of his text. Nevertheless, Ptolemy, unlike Euclid, incorporates many non-geometrical arguments into his account, including how we perceive colour,[499] why we see more clearly with both eyes, why visual acuity degrades with age,[500] how subjective judgments affect perception[501] and how we can fall prey to certain psychological miscalculations.[502] In fact, by attempting to explicate so much, Ptolemy does occasionally produce arguments that are difficult to harmonize—and sometimes he simply contradicts himself.[503] In general, however, his treatise represents a considerable improvement on the conclusions reached by his predecessors.

---

[498] The *Optics* can also be divided into those sections that deal with direct vision as it functions without error (*Opt.* 2.1-83) and those sections that deal with illusions (under which category Ptolemy considers both reflection and refraction, i.e. *Opt.* 2.84-5.87). For Ptolemy, illusions can either take place in sight or in the mind of the viewer [*quedam vero in visu et quedam in mente*] (*Opt.* 2.84). For a discussion of the classification of illusions and psychological effects according to this scheme, see LeJeune 1948: 15-17.

[499] Ptolemy considers colour to be a property belonging to objects, rather than something bestowed by either light or sight; cf. LeJeune 1948: 24-28; M. Smith 1996: 27. At *Opt.* 2.24-25, he seems to subscribe to the classical view of colours, namely, that all colours are some mixture of black and white, with red situated midway between the two; cf. n. 263.

[500] Ptol. *Opt.* 2.85-86.

[501] Ptol. *Opt.* 2.57-62 incorporates subjective judgments into size-perception; cf. M. Smith 1996: 95, n. 76, who notes the difficulty this presents for a fully geometric account of distance perception.

[502] For instance, Ptol. *Opt.* 2.90 mentions that objects appear smaller when they are adjacent to larger objects, whereas *Opt.* 2.123-127 discusses how colours can cause illusions and how painters utilize this feature to create the appearance of depth and distance on a two-dimensional surface. At *Opt.* 2.131, Ptolemy also examines the psychological illusion caused by imperceptible relative motions on a boat.

[503] Cf. n. 518-520 below.

Ptolemy's advances result from the application of both his considerable intelligence and his new technologies. Whereas the diagram was the sole tool that Euclid's *Optics* used for the explication and construction of vision, Ptolemy incorporates several different mechanisms and materials, including a ruler, glass cylinders and a bronze plaque designed to measure angles of incidence, reflection and refraction.[504] These tools expand the range of visual phenomena for which he provides an account and allow him to intervene in the visual process in ways that Euclid could not. In other words, Ptolemy attempts to rectify Euclid's exclusive reliance on diagrammatic technology by offering another set of technologies through which to think about vision. Ptolemy's mechanisms have led some scholars to consider him an experimentalist at core, a theorist fundamentally concerned with the physical, sensible world—[505] perhaps even a positivist,[506] guided by what Mark Smith refers to as a "fundamentally empirical approach."[507] Yet, while Ptolemy's investigations often include experimental trials—and the investigation of refraction in book five displays a unique commitment to empirical testing—Ptolemy incorporates many elements for which he provides no empirical

---

[504] For example, Ptol. *Opt.* 2.95 describes daubs of colour on the edges of a spinning potter's wheel coalescing as the wheel spins around, which helps him discuss both colours and the smallest perceivable unit of time; cf. *Opt.* 2.82 and 2.97. Ptolemy spends several books articulating the behaviour of mirrors, which had long been dealt within catoptrical texts (e.g. [Eucl.] *Catop.* and Hero, *Catop.*), and, more importantly, book five is devoted to explicating the behaviour of glass, which had not previously been treated systematically.

[505] For instance, de Pace 1981 argues that Ptolemy was Aristotelian rather than Platonic, by which she seems to mean that Ptolemy is more concerned with sensible reality than mathematical analysis; cf. M. Smith 1996: 18, who emphasizes this aspect of her argument, while also pointing out that Katsoff 1947 calls Ptolemy a "naïve empiricist."

[506] M. Smith 1996: 17-18 discusses various scholars who attempt to determine Ptolemy's philosophical affiliations. For instance, Duhem 1969: 14-18 suggests that Ptolemy was a positivist, while scholars such as Dambska 1971 and Taub 1993 consider Ptolemy to be a Platonist. Lammert 1920 considers him a Stoic.

[507] M. Smith 1996: 19. He argues, *contra* de Pace, that we could equally consider Ptolemy to be Platonic insofar as he wishes to rationalize empirical anomalies, and thus 'save the phenomena.'

justification, and geometry, not experimentalism, still reigns supreme.[508] The diversity of technologies incorporated into Ptolemy's explanations precludes the sole dominance of the diagram as a conceptual tool. Nevertheless, the particular tools that he uses to investigate vision still shape the way that he conceptualizes the anatomy and function of the eye. As a result, he proposes an ocular model that looks like a mirror, but this mirror is now convex and resembles the very experimental apparatus he uses to measure visual angles.

When Ptolemy begins his second book, his discussion seems to owe much to Aristotle, insofar as he first establishes what he calls the intrinsic, primary and secondary visual characteristics [*vere*, *primo*, *sequenter*][509] before explaining the mechanics of how we perceive these properties. While he is not simply reiterating Aristotelian ideas, Ptolemy is clearly drawing from his predecessor's approach, especially when he asserts that the visual faculty apprehends only "corporeality, size, color, shape, place, activity and rest" [*corpus*, *magnitudo*, *color*, *figura*, *situs*, *motus et quies*].[510] Yet, while these are the sole five visual properties, Ptolemy asserts that they are not visible *per se*. Instead, he clarifies, only "luminous compactness" [*lucida spissa*] is *intrinsically* visible [*vere*

[508] While Ptolemy frequently engages with both philosophical and physical arguments and tests certain visual phenomena experimentally, the *Optics* still predominantly uses geometry to explicate even these illusions.

[509] Ptol. *Opt.* 2.3. I am following M. Smith's 1996 translation of these terms. LeJeune 1989: 12 translates them as "vraiment," "immédiatement" and "médiatement."

[510] Ptol. *Opt.* 2.2. While they are not identical, these clearly parallel Aristotle's list of the five "common sensibles," namely "motion, rest, number, shape and magnitude" [κίνησις, ἠρεμία, ἀριθμός, σχῆμα, μέγεθος] at *De an.* 2.6.418a17; cf. n. 363 above. Moreover, Ptol. *Opt.* 2.16 clearly alludes to Aristotle's account in stating that light provides the 'form' to the 'matter' of colour, as it were [*ut forme coloribus quoque ut yle*]. At a basic level, it suffices to say that this set of concerns is completely absent from Euclid's account. For a discussion the Aristotelian features of Ptolemy's thought, see de Pace 1981.

videntur].[511] In other words, objects need light to be seen (whether they themselves supply it or simply derive it from another source), but must also be dense enough to impede the visual flux (which is why we cannot see the air, even though it is illuminated, and cannot see a rock in the dark, even though it is compact). Nevertheless, even luminous, compact objects are not visible by merely being illuminated. Rather, they are visible only insofar as they display what is *primarily* visible, namely colour.[512] All other properties, such as size, shape, place, etc., are *secondarily* visible and dependent on the first two characteristics. We could say that Ptolemy first establishes what is visible *qua* visibility and then what is visible accidentally. These metaphysical reflections support the geometrical discussions that follow.

For all the influence Aristotle had on Ptolemy's approach to the metaphysics of vision, the actual physical model that Ptolemy articulates looks very different from anything Aristotle proposes in either *De anima* or *De sensu*. Instead, Ptolemy posits that some type of visual flux [*visus*][513] exits the eye in the shape of a cone [*pyramis*][514] and strikes the visible object. Overall, the extended visual flux functions essentially as a form of touch, whereby information about the visible object is somehow transmitted, or simply

[511] Ptol. *Opt.* 2.4; cf. 2.9, 2.19.

[512] Ptolemy holds colour to be what is primarily visible, since all objects, even the sun, can only be seen insofar as they display some colour, while colour without illumination is invisible. Intrinsic and primary visible properties are thus mutually dependent: nothing is seen without light, but even light itself, while intrinsically visible, is not visible *per se*, but only insofar as its luminosity and brightness is a type of inherent whiteness. We can therefore understand luminous compactness to be the *sufficient* cause of vision, while colour is the *necessary* cause of vision.

[513] The term *visus* is most likely a translation of the Greek ὄψις *via* the Arabic, but this cannot be confirmed. Both LeJeune 1989 and M. Smith 1996 render the word as 'visual flux.'

[514] The Latin *conus* is only used once, at Ptol. *Opt.* 2.105, but it is clear from all of the geometrical proofs that the *pyramis* has a circular base; cf. LeJeune 1948: 33-34, esp. n. 8; 1957: 21.

'felt' along its length.[515] This "affection" [*passio*][516] thus provides information about colour, from which the secondary properties, such as shape, distance, etc., are discerned.[517] That being said, Ptolemy sometimes speaks as though this visual flux were composed of stable visual rays [*radii*],[518] while at other times it functions like a series of projectiles;[519] other times still some substance seems to be perpetually flowing from the eye.[520] Thus, while he promotes an extramissionist theory, he posits different physical behaviours according to the proximate needs of his immediate argument.

---

[515] Ptolemy frequently relies on arguments that establish vision as a sense akin to touch (see esp. Ptol. *Opt.* 2.7-8; 2.67; 2.88), which would seem to imply that the visual flux maintains direct contact with the eye. To my mind, it is easier to understand how a model of vision based on touch harmonizes with a rigid-ray theory than with a projectile theory.

[516] Ptol. *Opt.* 2.22 claims that visual information comes from an "affection" [*passio*] in the visual flux, which is more than likely a translation of the Greek πάθος.

[517] Ptol. *Opt.* 2.26. By attributing depth perception to ray length, Ptolemy concludes that it is possible to perceive distances when viewing objects with a single eye. Ptolemy also incorporates colour into our subjective miscalculations about the distance of visible objects (*Opt.* 2.123-127, see n. 502 above).

[518] Although Ptolemy rejects Euclid's discrete rays as an analytic fiction (see below), he frequently makes comments that contradict this assertion. For instance, he mentions that "each ray terminates at its own unique point" (*Opt.* 2.20); and he asserts that a large angle contains *more* visual rays while discussing the accumulation and concentration of rays (*Opt.* 2.4). Moreover, like Euclid before him, Ptolemy's geometrical explanations of motion-perception often rely on the concept of a rigid, stable ray that reaches all the way to the object, arguing that objects appearing stable "when the endpoint of one and the same ray apprehends sensibly one and the same spot on the object" [*terminus unius et euisdem radii comprehendit de subiecta re unam et eandem partem in sensu*] (*Opt.* 2.76). He relies on a similar explanation of vertigo, namely that it can be caused "by a sweep of the visual rays" [*revolutio radii*], which naturally would have to be extended like sticks (*Opt.* 2.121). Even if all of these arguments are explained by interpreting the ray as a mathematical fiction (which seems difficult, especially in the arguments about motion), the idea of a rigid ray would bring Ptolemy very close to the Stoic explanation of vision, which requires *pneuma* to extend from the eye to the object like "walking stick" [βακτηρία] (see Gal. *De plac. Hipp. et Plat.* 7.7; cf. p. 240 below). For the Stoic elements of Ptolemy's theory, see M. Smith 1988: 195-196.

[519] Ptolemy uses a dynamic, projectile model to explain the equal angle law of reflection (*Opt.* 3.19-20), as well as to explain why visual acuity degrades over distance (*Opt.* 2.20) and after bouncing off of an object, such as a mirror (*Opt.* 2.19, 3.22); cf. Hero, *Catop.* 2; [Arist.] *Pr.* 16.13.915b18-35; see LeJeune 1989: 98, n. 32. It is difficult to understand how the dynamic model of projection would account for transmitting information back to the eye, since, once a javelin has been thrown, it has no contact with the hand that threw it.

[520] Ptol. *Opt.* 2.76 talks about "succeeding rays" [*posteriores radii*], as if there were a constant flow of visual flux streaming outward from the eye. Moreover, the visual flux moves extremely quickly (*Opt.* 2.73), can pick up colour from the transparent media through which its travels—including both air (*Opt.* 2.19) and fabric (*Opt.* 2.107)—and can carry the eye's moisture along in its stream (*Opt.* 2.87). Like the

Although Ptolemy presents many ideas similar to Euclid's, he distinguishes his theory in several key ways.[521] Most importantly, whereas Euclid believed that an actual, physical ray projected from the eye, Ptolemy argues that a "ray" is merely an analytic fiction, a convenient geometrical tool that can be used to understand perspective and distance-perception. For him, the visual flux cannot be composed of discrete lines, but must be *continuous*. In fact, he criticizes Euclid on precisely this point:

> *Oportet autem cognoscere quod natura visibilis radii in his que sensus consequitur, continua est necessario et non disgregata. Si vero posuerimus mathematicas demonstrationes et constituerimus radios visus tamquam rectas lineas, magnitudines utique magne que sunt in distantia equali distantie qua parve res non videntur propter parvitatem earum, apparebunt manifeste, quod non accideret si visibiles radii in illo loco minuerentur et disgregarentur.*
>
> …it must be understood that, as far as visual sensation is concerned, the nature of visual radiation is perforce continuous rather than discrete. But if we set up *mathematical demonstrations* and treat the visual rays *as if they were straight lines*, [it follows that] large magnitudes lying the same distance away as small ones that are invisible because of their smallness will still be clearly seen (Ptol. *Opt.* 2.50, emphasis mine).[522]

As Ptolemy begins to suggest, according to Euclid's model, proximity cannot offer any greater resolution, since a line can only ever touch an object at a single point, whether this occurs a few inches from the eye or several miles away. Furthermore, since only those points are visible on which rays fall, objects should actually appear as mosaics, not

---

projectile model, the flux model produces similar questions about how information is transmitted back to the eye, since a river only flows in a single direction. Moreover, it conflicts with the explanations of motion perception mentioned above; see n. 518 above.

[521] Whereas Euclid's geometrical account of vision has no place for light—in part because his geometrical articulation of sight does not make room for it—Ptolemy recognizes that visual flux cannot see objects on its own and must somehow interact with light in order to perceive any visible properties. While Ptol. *Opt.* 2.1 indicates that these two substances "interact" [*communicare*] and "mix" [*cooperari*], the discussion of this process would likely have been contained in the lost first book.

[522] All translations of Ptolemy's *Optics* are adapted from M. Smith 1996.

as whole entities, as Euclid argues.[523] Ptolemy concludes his attack with a far more withering critique, however—one that gets at the heart of the problematic relationship between Euclid's geometrical line and the physical object it supposedly represents and that we dealt with in the last chapter. That is, by their very definition, Euclid's rays do not subtend any angle, and thus, according to his own definitions, even the small pin points on which the rays fall should not actually be visible, no matter how many of them occupy the field of vision. Therefore, Ptolemy concludes, the visual flux must instead be continuous, not discrete.

In many ways, Ptolemy has thus explicitly attempted to free himself from using the "mathematical demonstrations" of the diagram as the sole cognitive tools through which to comprehend vision, emphasizing that the properties displayed by geometrical lines simply do not sufficiently explain the physical phenomenon. Instead, he posits that visual resolution depends not on the *number* of rays that strike a given object, but on the *strength* of the visual flux itself. This strength can be affected in two main ways: 1) distance (the farther the visual flux extends, the weaker it gets); and 2) concentration (the visual flux is most concentrated along the centre of the visual axis).[524] Combined, these explain why both distant objects and those appearing in one's peripheral vision are less distinct.[525] By conceiving of the visual cone as an area with relative densities, however,

---

[523] Ptol. *Opt.* 2.51. Ptolemy does not acknowledge that Euclid argues that visual rays fill these gaps by oscillating quickly back and forth; cf. [Eucl.] *Opt.* prop. 1, B.

[524] Ptol. *Opt.* 2.20.

[525] Ptol. *Opt.* 2.28 suggests that we have two eyes merely to strengthen our visual acuity, not to allow depth perception. While Ptolemy supplies multiple factors contributing to the visual flux's strength, he does not provide a hierarchy of their relative effects. This amorphousness characterizes many of Ptolemy's explanations, which often bring multiple variables to bear on a single visual effect, while leaving their specific interrelations underdetermined.

Ptolemy re-imagines the triangles on the page as extra-geometrical entities. He moves beyond the conceptual apparatus provided by his geometrical diagrams.[526]

5.2 Ptolemy's Ruler and the Visual Axis

Other sections in the *Optics* display Ptolemy's experimental methodology more clearly, whether he uses technologies to carefully measure optical phenomena, verify his conclusions or simply gather information. The first such technology is his ruler, a version of a *dioptra* mechanism no more complex than a board with a few pegs on it. Ptolemy uses this apparatus to investigate and explain *diplopia*, or 'double-vision.' According to his account, this phenomenon occurs when the axes of the two visual cones do not align, and the same object occupies a different *relative* position in each of our visual fields. Ptolemy's account is the first to include any mention of the "visual axis," and it therefore allows for the directionality of vision in a way that was never possible for Euclid. Yet, since many different objects occupy this field of vision at any given moment and we can only ever focus on a single point at any given time, *diplopia* occurs in our peripheral vision constantly—whether or not we take note of it. Ptolemy thus needs to stabilize the slipperiness of the phenomenon by providing some type of conceptual structure. In order to do so, he builds an apparatus:

> *Constituatur regula brevis, et duo cilindri subtiles, longi, stantes super eam ad rectos angulos. Et sit distantia alterius ab altero et ab extremitatibus regule moderata. Et ponatur altera extremitatum inter oculos, ita ut cilindri sint super rectam lineam stantem super distantiam que est inter oculos, ad rectos angulos.*

---

[526] This is not to say that distance and density cannot be treated geometrically (although Ptolemy does not do so), but that the bare field of vision pictured in a diagram does not itself offer these concepts. Ptolemy must apply them *to* the diagram, rather than deriving them *from* the diagram.

> Let a short ruler be set up, let the two long, thin cylindrical pegs be stood vertically upon it, and let the distance between the two pegs themselves and between the pegs and the edges of the ruler be moderate. Let either edge of the ruler be placed between the eyes so that the pegs lie in a straight line at right angles to the line connecting to the eyes (Ptol. *Opt*. 2.30).

This implement is quite simple in construction, more or less a long ruler with two moveable pegs, one white and one black, standing upright upon it.[527] While Ptolemy's ruler bears a family resemblance to other types of *dioptrai*,[528] it functions in a unique way: it does not sight objects *beyond* the mechanism (as these implements usually do), but directs both eyes to the pegs *inside* the mechanism. He can thus use it to investigate binocular vision and the illusion of *diplopia* (fig. 21):

[527] While Ptolemy does not refer to his device as a *dioptra*, as LeJeune 1989: 28, n. 37 has pointed out, his apparatus bears considerable similarities to a *dioptra* of Hipparchus, described by Archimedes, which is used to measure the visual angle of the sun, as well as the angle subtended by the cornea itself; cf. Archimed. *Arenar.* 137-143. Lewis 2001: 41-42 provides a description and a drawing of this device; cf. Hultsch 1899; Neugebauer 1975: 657-9. For LeJeune's account of Archimedes' dioptra, see LeJeune 1947: 31; cf. M. Smith 1996: 83, n. 50. For similar devices mentioned in other ancient texts, see Ptol. *Almag.* 5.14; Papp. *Comment.* 90-5; Procl. *Hyp. ast. pos.* 4.72-73, 87-99.

[528] By definition, a *dioptra* is any device through which you can look, and a brief look its lexical uses shows that can describe implements as diverse as sheets of talc used as windowpanes and medical specula. More commonly, however, a *dioptra* is a device used in astronomy, ballistics and engineering for measuring visual angles and sighting straight lines. It can allow you to judge whether something is level, measure the arc of a celestial formation or gage the height of a wall from a distance. Hero's *Dioptra* is the *locus classicus* for information about these mechanisms, and at *Dioptr.* 2, he lists multiple uses, including for the construction of aqueducts, buildings and harbours, conducting astronomy, calculating distances for geographical mapping and judging the height of enemy ramparts from a distance in order to build appropriately-sized siege engines. As one can imagine, these multiple functions required different design features. Hero, *Dioptr.* 1 even laments the variety of *dioptrai* available in his day, while providing two different models of his own. Hero, *Dioptr.* 3 describes the first version, which involves two perpendicular geared plates that can establish both a horizontal and a vertical angle of sight in a manner especially applicable for astronomy. Unfortunately, the text breaks off in the middle of Hero's description, but a rough picture of the device can be gleaned from what remains, as well as from references to the mechanism found later in the text; cf. Lewis 2001: 260-261 for a similar argument and reconstruction Hero, *Dioptr.* 6 describes the second version, which requires a long sighting board with an internal water level. Having set the level, one can look through the sighting mechanism and down along the board in order to spot a sliding target positioned along a measuring staff in the distance. This will establish the relative gradient of two locations—information that is especially useful when constructing aqueducts; cf. Lewis 2001, who provides an overview of Greek and Roman surveying devices.

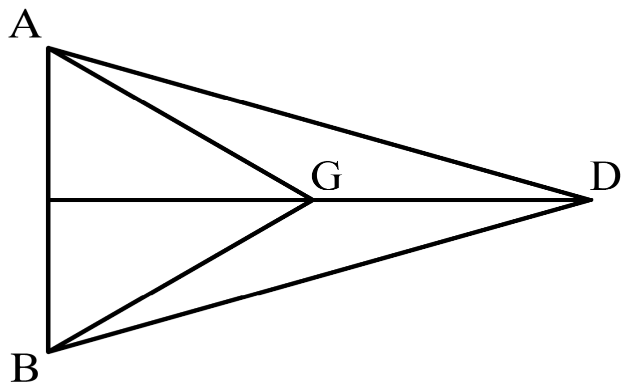

Fig. 21 Ptolemy's Account of *Diplopia* (*Opt.* 2.33)[529]

Sint capita piramidum puncti A, B, *et sit* B *super dextrum oculum et* A *super sinistrum. Sintque super lineam perpendicularem que est super* AB *ad rectos angulos, duo cilindri erecti, videlicet* G, D. *Et producantur ad eos ab omni capite duarum piramidum radii* GA, GB, DA, DB. *Et tendamus prius cum visu nostro ad* G *qui est propinquor*.

Erunt ergo AG *et* BG *super ipsos axes. De residuis vero duobus radiis* AD *erit unus de sinistris radiis. Manifestestum quoque est quod* BD *est unus de dextris radiis. Vnde oportet* G *quidem videri in uno loco, eo quod unusquisque axium est ordine similes alteri*; D *vero debet videri in duobus locis, quoniam* ad *est radius sinister de radiis sinistri oculi, radius autem* BD *dexter de radiis dextri oculi. Cum ergo texerimus sinistrum oculum, abscondetur sinister; et cum dextrum oculum texerimus, abscondetur dexter.*

Let points A and B in the figure be the vertices of the visual cones, and let B lie at the right eye and A at the left. Let two pegs, G and D be erected vertically upon the line [GD, which is] perpendicular to AB, and from each vertex of the two visual cones let rays GA, GB, DA and DB be extended to the two pegs.

AG and BG will therefore lie upon the axes themselves. Of the remaining two rays, however, AD will be one of the left-hand rays [in the cone whose vertex is at A], and it is obvious that BD is one of the right-hand rays [in the cone whose vertex is at B]. It necessarily follows, then, that G is seen at one location, insofar as each of the axes corresponds with the other. On the other hand, D must be seen at two locations, since AD is one of the left-hand rays of the left eye, while ray BD is one of the right-hand rays of the right eye. Thus, when we cover the left eye, the left-hand [member of the doubled image] will disappear, and when we cover the right eye, the right-hand [member] will disappear (Ptol. *Opt.* 2.33).

[529] All diagrams from Ptolemy's *Opt.* are based on those in LeJeune 1989.

This experiment is easy enough to reconstruct even without Ptolemy's ruler. Place two pens, pencils or fingers a few inches apart from each other in the straight line extending out from your nose (on the model of the above figure). Focusing on the near 'peg' will cause the farther one to double. In turn, focusing on the farther peg will cause the nearer to double. In either of these scenarios, if you close one of your eyes, one of the doubled images will disappear. In this regard, Ptolemy's account seems accurate.

By using this simple mechanism to investigate binocular vision,[530] Ptolemy can proceed rather systematically. First, he examines what happens when both eyes focus somewhere beyond the pegs (both pegs are doubled) (*Opt.* 2.36-37); then he examines what happens when the pegs are directly in line with each each (*Opt.* 2.38);[531] then when they are slightly to the left of the centre axis; then slightly to the right (*Opt.* 2.39-40); then when the pegs are spaced wider than the eyes (*Opt.* 2.41-42); then narrower (*Opt.* 2.43-44).[532] In other words, the geometry of the ruler mechanism structures Ptolemy's investigation, so that when he has proceeded through the obvious spatial permutations of the pegs, his discussion of *diplopia* comes to a close (at least in this section). For Ptolemy, 'explaining binocular vision' functionally means 'using the ruler.' This experimental apparatus thus mediates his interaction with vision, bending the experience of sight around its own contours.

---

[530] In order to confirm his conclusions about binocular vision, Ptolemy incorporates another apparatus at *Opt.* 3.43, this time a board with coloured lines marked along both the axes of vision and the axes of apparent location.

[531] In this case, the proof supplied by the text seems to have been lost, or at least severely corrupted, although the diagram remains; see M. Smith 1996: 86, n. 54.

[532] Ptol. *Opt.* 3.25-42 returns to the mechanism to make further conclusions about binocular vision and distance-perception.

This section is not the only place where Ptolemy discusses binocular vision. He returns to the subject at *Optics* 3.25, where his ruler plays a more crucial role in both structuring his experience of vision and conceptualizing the physical mechanism of spatial location. Here, Ptolemy wants to explain a feature left over from his earlier discussion: if the eyes never see an object in the same spot in their respective visual cones, how do they know where any object actually is? How can we determine the actual location of any given object, if one visual cone will always perceive the object in a place different from the other? In order to answer this, Ptolemy simply sets up his *dioptra* again, using its structural geometry as an empirical guarantor of his claims. He posits that in order to determine the actual location of a visible object, we must do so with reference to a line, called the "common axis" [*axis communis*], shared by both the visual cones. It proceeds along the straight line running orthogonal to the plane of the eyes (shown as GD in the diagram below (fig. 22):

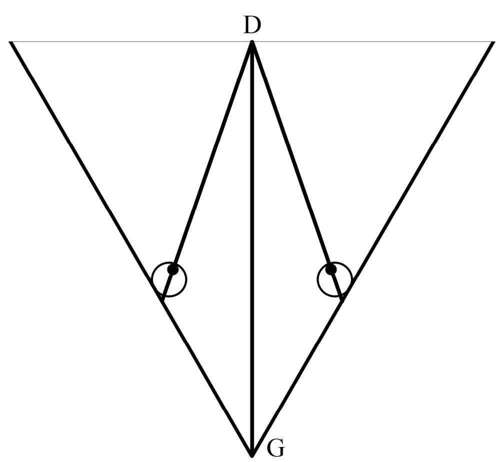

Fig. 22 Ptolemy's *Axis Communis* (*Opt.* 3.35)

Et cum hec ita fuerint sicut diximus, convenit ut natura coequet diversitatem que est inter duos axes et congreget eos secundum situm rei vidende. Cadunt ergo utrique super eam a principio quod est inter eos et

> *est illud in quo debet coniunetio capitum piramidium fieri. Et distantia eius ab illis est equalis, et eorum sensibilitas est communis. Fitque hoc secundum quod accidit in una via de eo quod medium est est inter utraque latera, quoniam impossibile est ut magnitudo que est opposita eis, conservet situm similem penes unumquemque axium. Res enim que apparet opposita utrisque oculis, non est perpenicularis super utrosque axes. Quomodo enim possumus hoc arbitrari, cum esse in medio, sicut diximus, et est distantia eius proportionalis? Qui rationabiliter debet vocari axis communis.*
>
> Since all this is as we have claimed, it follows that nature equalizes the disjunction between the two visual axes and joins them according to the location of the visible object. Therefore, both of them fall upon the object from the apex [*principium*], which lies between them and is located where the vertices of the visual cones ought to intersect. This *principium* is equidistant from those axes, which have a common sensibility. And let there be a second thing which falls in line from that which is in between both sides, because it is impossible for an object facing the visual axes to maintain the same orientation with respect to each of them. In fact, an object directly in front of both eyes is not orthogonal to both axes. How, then, can we determine spatial disposition if each of the axes is inclined to the other, unless, as we said, we so do on the basis of some intermediate reference line whose distance [from the axes] is proportional [throughout]? Reason dictates that this reference-line be termed the 'common axis' (Ptol. *Opt.* 3.35).

As LeJeune indicates, despite its usefulness, there is little empirical justification for positing that any such entity as a "common axis" exists.[533] While its usefulness may be what prompts Ptolemy to propose such a reference line, we should not fail to note that he has an actual ruler lying precisely in that position (see fig. 21). In other words, he has incorporated a material aspect of his apparatus into the mechanism of the eye. By structuring his investigation of binocular vision on his ruler, Ptolemy treats his

[533] M. Smith 1996: 144, n. 38 suggests Ptolemy might be referring to the optic chiasma, i.e. the crossing of the optic nerves behind the eyes, although *Opt.* 3.61-62 seems to indicate that Ptolemy simply means the so-called "Governing Faculty." There is even less justification for the accompanying law of binocular vision that relies on the hypothesized common axis; cf. Ptol. *Opt.* 3.33-61. Ptolemy states that objects in front of the focal point are doubled and do not appear in their actual locations, whereas objects placed either behind the focal point, or along its perpendicular will be seen in their actual location by both eyes (by a fusing of their images). LeJeune 1948: 156-160 discusses this law, but notes that its formulation, as well as its empirical support, is less than rigorous, claiming (quite weakly) that the law is "not purely arbitrary."

experimental device as the mechanism by which the eye *itself* determines spatial location. The technologies with which he investigates vision infiltrate his conceptual model.

5.3 Ptolemy's Anatomical Geometry

An even more pronounced example of conceptual slippage occurs when Ptolemy discusses reflection and utilizes another apparatus for his investigation. In books three, four and five, Ptolemy investigates two new types of visual illusion: reflection and refraction. While he distinguishes between the two, he argues that they are merely special case of one another: both illusions arise from the visual ray breaking in a secondary surface. This breakage can either be total (reflection), or partial (refraction).[534] For my present purposes, I will focus only on reflection.

To begin his investigation of this phenomenon, Ptolemy posits three principles: 1) the objects visible in mirrors are seen by the extension of the visual ray that reaches them through reflection; 2) objects are seen along the cathetus of reflection;[535] and 3) the angle of incidence equals the angle of reflection.[536] In order to provide support for these claims,

[534] Ptol. *Opt.* 3.1-2. Refraction occurs when the visual ray penetrates bodies, which breaks the ray to some degree. In contrast, reflection involves a complete breaking of the ray by objects that it cannot penetrate. Ptol. *Opt.* 3.15 provides an account of why we do not notice this 'breaking,' even though we might be expected to notice when our visual flux strikes a dense, illuminated object, such as a mirror. His explanation relies on the fact that the portion of the mirror that each individual ray strikes has no breadth, and therefore the eye cannot calculate an angle based on this interaction, and thus cannot gauge that its trajectory has been changed. Not only is this account confusing, it seems to contradict Ptolemy's arguments against Euclid's discrete ray theory; cf. M. Smith 1996: 137, n. 15. For examinations of Ptolemy's theory of reflection, see G. Simon 1988: 148-165; LeJeune 1957: 33-46, 70-111; M. Smith 1996: 35-42.

[535] In other words, an object will appear to be situated where the visual ray and a perpendicular line dropped from the object *would* intersect if both the ray and the line continued straight through the surface of reflection.

[536] Ptol. *Opt.* 3.3.

Ptolemy does not rely wholly on geometrical proofs,[537] and he instead looks for experimental confirmation. The first two principles are relatively easy to confirm,[538] but the third principle, the equal angle law of reflection, is the most difficult to verify. In order to do so, Ptolemy constructs another apparatus, this time a bronze plate marked with angles (fig. 23):[539]

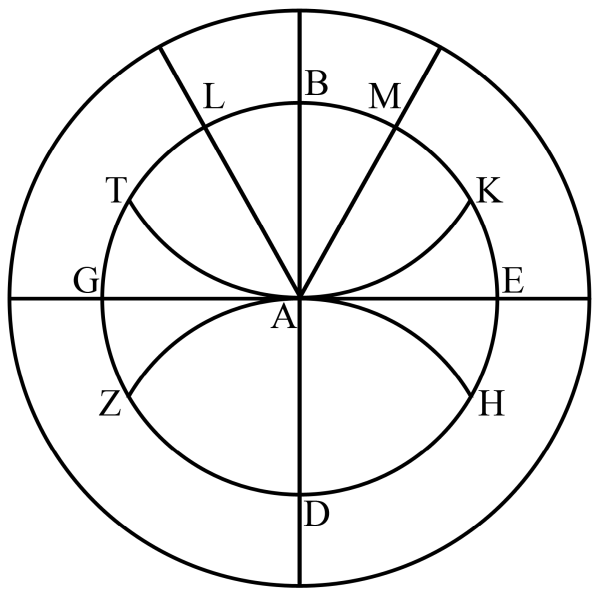

Fig. 23 Ptolemy's Bronze Plaque (*Opt.* 3.8-9)

[537] Although he makes no mention of his predecessors' formulations of these laws, Ptolemy did not invent them. Different versions, which do rely on geometrical proof, appear at Hero, *Catop*. 1-54, Archimed. fr. 19 and [Eucl.] *Catop*. def. 3, 4 and prop. 1, 16-18. For an examination of the relationship between Ptolemy's formulation and those of his predecessors, see LeJeune 1957: 33-69; cf. M. Smith 1996: 35, n. 6. LeJeune 1957: 54-67 considers the pseudo-Euclidian *Catoptrics* to be a compilation assembled after Ptolemy's death; cf. Heiberg 1882.

[538] Ptol. *Opt.* 4. He tests the first principle simply by covering any given point along the line of reflection (most easily done at the point of reflection in the mirror). This confirms that the line of sight is continuous from the eye to the object by way of the mirror. The second principle is more difficult to confirm and requires placing a long rod perpendicular to the edge of a mirror to verify that reflection occurs along this cathetus, physically represented by the rod. The explanation of the second principle is difficult to understand (most likely because of a garbled translation), but like LeJeune 1989: 89, n.7, I take Ptolemy to be providing empirical evidence for both principles in this section; cf. LeJeune 1957: 36-37.

[539] Before utilizing the bronze plate, Ptol. *Opt.* 3.6 first offers empirical justification for the equal angles law of reflection through an experiment: he suggests facing a mirror (while being relatively close to it) and then crossing your eyes so that one eye sees the reflection of the other and *vice versa*; the two individual images will thus fuse together into one (according to the law of equal angles); cf. M. Smith 1996: 133, n. 6; LeJeune 1989: 90, n. 10. The proof contains some textual difficulties, which LeJeune 1957: 37-41 attempts to clear up.

> *Constituatur planca rotunda, ut hec cuius centrum sit* A*, sitque erea, moderate quantitatis. Et sint utreque superficies eius coequate quanto magis diligenter coequari possunt, sintque extremitates circumferentie eius rotunde lenite. Et protrahatur in altera superficie eius paruus circulus super centrum* A *et eit* BDGE. *Et protrahantur in ea duo diametri secantes se invicem ad rectos angulos et sint* BD, GE. *Et dividatur unaquaque quarta pars circuli per nonaginta partes. Et sumantur duo puncti* B, D *tamquam centri, et protrahantur per distantias* BA, DA, *due sectiones duorum circulorum super quas sint* ZAH, TAK.
>
> *Et constituantur tres regule ferree, subtiles, parve, quadrate, recte. Quarum una maneat recta, et leniatur unum ex lateribus suis, ita ut appareat tamquam speculum clarum. Et curuentur relique due regule, ita ut curua superficies unius et concava superficies alterius sint super sectionem circuli equalis circulo* BGDE*, et leniantur due superficies istarum regularum ut fiant tamquam duo specula.*
>
> Let a round, bronze plaque of moderate size, such as the one below, be set up, and let A be its centre. Let both faces be planed down as carefully as possible, and let its edges be rounded and polished. Then let a small circle be inscribed at centre point A on either of its faces, and let it be BGDE. On this same face let two diameters, BD and GE, be inscribed to intersect at right angles; and let each quarter circle be divided into 90 degrees. Finally, let the two points B and D be taken as centre points, and, using BA and DA as radii, let the two arcs ZAH and TAK be inscribed.
>
> Now let three thin, small, square, straight sheets of iron be formed. Let one of them remain straight, and let one of its sides be polished so that it appears as a clear mirror. Let the remaining two sheets be curved in such a way that the convex surface of the one and the concave surface of the other [taken together] form a circular section equal to circle BGDE, and let the two [respective convex and concave surfaces] of these sheets be polished so that they are made into two mirrors (Ptol. *Opt.* 3.8-9).

Ptolemy's apparatus allows a reflective surface (or a tangent thereof) to run horizontally along the centreline at A, whether that surface is a plane, convex or concave mirror. Ptolemy then adds a sight with a hole in it—which can be slid along the circumference of the bronze plaque. In order to test the equal angles law of reflection, he simply places the sight at L, looks through it and places an object at M so that it reflects at point A. He then manually measures the angles LAB and MAB to verify that they are equal. Since the experiment confirms that the angle of incidence and the angle of refraction are indeed the same regardless of whether he installs a plane, convex or concave mirror, Ptolemy demonstrates empirically that the equal angle law of reflection holds generally.

Ptolemy has received much praise for this empirical confirmation of a physical law, but it is unclear to my mind just how precise this mechanism could have been. Moreover, the remainder of his explication of mirrors, whether plane, convex or concave, almost exclusively involves geometry, and leaves experimentation aside.[540] For all of Ptolemy's commitment to empirical methods, he does not revisit the bronze plaque apparatus until *Opt.* 4.71, when he tries to explain how images sometimes appear to coalesce with the mirror's surface.[541] Therefore, whereas his ruler structured his investigation of binocular vision, the bronze plaque apparatus does not structure his investigation of reflection as much as authorize the geometrical proofs that follow. Nevertheless, even the limited use of this technology to explicate curved mirrors seems to have had a deep impact on Ptolemy's conception of the physical eye. In fact, his physiological model almost directly embodies his experimental device.

The first intimations of this occur when Ptolemy explains how the visual cone interacts with the eye. Euclid all but ignores this relationship, stating merely that the visual cone has its origins "at," or "on the eye" [πρὸς τῷ ὄμματι].[542] In contrast,

---

[540] Ptol. *Opt.* 3.73-75 uses geometry to demonstrate that plane mirrors only produce a single image. Similarly, they do not distort the distance of that object, nor do they misrepresent its size or its shape (*Opt.* 3.76-90)—although they do invert left and right (*Opt.* 3.91-96). He uses geometry to demonstrate that convex mirrors only produce a single image, that the image moves along with its object and that these mirrors do in fact distort size, distance and shapes—albeit according to the laws of reflection that he articulates (*Opt.* 3.97-132). Finally, in book 4, Ptolemy uses geometry to demonstrate that concave mirrors can produce multiple images of the same object (*Opt.* 4.1-40); that they distort the distance, size and shape of the object (*Opt.* 4.10-141), but will sometimes avoid inverting an object's left-right orientation (*Opt.* 4.142-155).

[541] For an analysis of this proposition and its inherent difficulties, see M. Smith 1996: 40-41.

[542] [Eucl.] *Opt.* def. 2, B. The A manuscripts state that the cone has its vertex "in" or "on the eye" [ἐν τῷ ὄμματι].

Ptolemy actively attempts to combine the visual cone with his physiological model, declaring the eye to be a perfect sphere, the *centre* of which provides the cone's vertex.[543] That being said, he neither argues for the eye's perfect sphericity, nor confirms it experimentally. Instead, he simply accepts that the eye's centre is the source of the visual flux, as though this were simply a natural and unproblematic conclusion. In the third book, however, he draws an analogy to support this, comparing the eye to a convex mirror. This mirror instantiates the same geometry as before:

> *Radii enim principio, cuius positio est intus super centrum figure sperice, fiunt omnes perpendiculares super pupille superficiem que suscipit naturam curui specula cum figura et lenitate sua.*
>
> Indeed, the rays that pass through the cornea and radiate to the pupil from the origin-point, which lies within the ocular sphere at the centre point, all form perpendiculars to the surface of the pupil, *which assumes the nature of a convex mirror in terms of its shape and smoothness* (Ptol. *Opt.* 3.16).

While this may seem little more that a colourful image, perhaps in line with the long history of comparing the eye's surface to a mirror, Ptolemy returns to the comparison in book 4, where he uses the geometry of the convex mirror to explain how we orient objects in our visual field.

In this section, Ptolemy tries to provide a solution for the following problem: if all the visual rays extend from a single (geometrical) source, how we tell which direction they extend? If the source of the visual cone has no magnitude, it has no means of sensing the directionality of the rays projecting from it, since only triangulation can determine direction (e.g. think of why we need two ears).[544] As such, Ptolemy tries to propose a

---

[543] Ptol. *Opt.* 2.20; 2.26; 3.35; cf. See LeJeune 1948: 51-57. Ptol. *Opt.* 3.35 also suggests that a *principium* exists *behind* the eyes where both visual cones meet.

[544] Euclid potentially faces the same physical problem, but simply posits in *Opt.* def. 6 that "those things which are seen by rays more to the right appear more to the right, while those things which are seen by rays

physical mechanism involving the spherical geometry of the cornea and uses a concave mirror as an apparatus to demonstrate it (fig. 24):

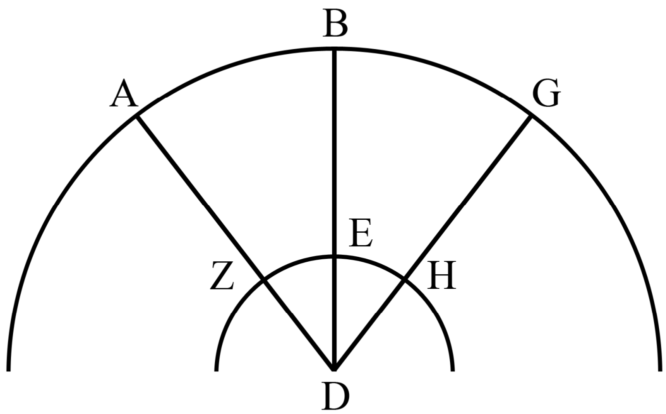

Fig. 24 Ptolemy's Eye (*Opt.* 4.4)

> *Esto sectio circuli in speculo concavo que est* ABG; *cuius circuli sit centrum* D. *Et protrahatur in speculum perpendicularis* BD. *Sitque uisus punctus* D, *et sit punctus* E *medium aspicientis*. *Et constituatur in superficie ista super centrum* D *circumferentia* ZEH *secans latitudinem aspecientis. Et protrahantur due linee* AZD, GHD. *Erunt ergo perpendiculares super speculum. Omnes igitur radii cadentes a puncto* D *super circumferentiam* ABG *refringuntur in se ipsos ad punctum* D, *et comprehenduntur et sentiuntur per loca super que cadunt a visu radii similes* DA, DB, DG*, et comprehenduntur et sentiuntur per punctos* E, Z, H.
>
> Let ABG represent the arc of a circle lying on a concave mirror whose centre is D. Let BD be drawn normal to the mirror. Let D be the centre of sight and E the midpoint [where the axis of the visual cone intersects the surface] of the cornea. In this plane, on centre point D, let arc ZEH be drawn through the corneal surface. Then, let the two lines AZD and GHD be drawn. They will therefore be perpendicular to the mirror. Hence, all rays emanating from point D to arc ABG are reflected back on themselves to point D. Moreover, they are apprehended and sensed according to the spots at which rays like DA, DB, and DG strike [as they are] projected from the eye, and they are actually apprehended and sensed according to points E, Z and H (Ptol. *Opt*. 4.4).[545]

more to the left appear more to the left." In other words, he simply lets the geometry on the page stand in for the mechanism at work in the eye, even if this presents physical difficulties.

[545] M. Smith 1996: 137, n. 16 suggests that Ptolemy takes sight to function through ἔμφασις, just as Democritus did when he compared the eyes to mirrors, but the above passage offers too little support for Smith's conclusion.

The theory Ptolemy is here putting forward is somewhat confusing. He suggest that all the visual rays extending from the eye's geometrical centre will strike the convex mirror perpendicular to its tangents. Therefore, according to the law of reflection, these rays will be reflected directly back to the vertex of the visual cone. In other words, if a concentric spherical concave mirror should surround the eye, the mirror should reflect an image of the vertex back to itself. In this instance, it should be impossible to discern which direction is which (since all rays would appear at the same point). Nevertheless, Ptolemy wants to hold that *even* in this extreme instance, we would still be able to discern left from right. Thus, he argues that we must perceive A to be farther to the left than G insofar as we apprehend the reflected visual ray DA at point Z *on the cornea*, rather than at point H.[546] Similarly, we perceive G to be farther to the right than A since we apprehend the reflected visual ray DG at point H on the cornea. Thus, having provided a mechanism to determine spatial orientation in this most extreme instance, *a fortiori* he has supplied a mechanism for all other instances.

Even a simple glance at Ptolemy's diagram of the eye displays the resemblance his geometrical model bears to his bronze apparatus: both work with concentric circles; both measure angles of incidence and refraction; both involve concave mirrors; and most importantly, both make the geometrical *centre* of the apparatus the critical point of operation. As "natural" as this may seem, no other theory encountered so far has posited this feature about the eye. Empedocles made pores the eye's operative feature; Alcmaeon and Anaxagoras made its surface the site of vision; so too did Democritus, although like Aristotle, he also attributed a role to the interior of the eye. Even geometers proposing a

[546] Cf. Ptol. *Opt.* 2.27, which also deals with how the eye determines spatial orientation.

visual cone still do not make this assertion: Euclid places the vertex at the *front* of the eye, whereas Archimedes seems to have placed it somewhere behind the eye.[547] In short, Ptolemy is the first theorist to make the eye's geometric centre its operative part. The fact that he investigates vision with an apparatus embodying just this geometry suggests that his implement has provided him not only with empirical data, but a visible heuristic on which to structure his anatomical assumptions. Once again the eye has been declared to function "like a mirror," but this now means something quite different than before. Whereas for Democritus, it meant that the eye sees by receiving an image, for Ptolemy, it means that the eye sees by operating according to the geometry of the bronze apparatus. Both thinkers use the mirror to conceptualize the eye, but a mirror now embodies a different set of physical assumptions. It is a different technology.

5.4 Galen's Geometrical Anatomy

In the same century that Ptolemy wrote his *Optics*, Galen composed multiple treatises concerning vision.[548] Several of them, including *On Demonstration* and *On Vision*, have been lost,[549] but three remaining treatises still provide a wealth of evidence. The first two works, *Anatomical Procedures* and *On the Usefulness of the Parts*, supply the most detailed descriptions of ocular anatomy, while *On the Opinions of Hippocrates and Plato* concentrates on describing the physical mechanism of vision. In all these texts, however, Galen weds precise anatomical details to a larger philosophical theory, and thus

[547] Archimed. *Arenar.*137-143 does not actually identify where the vertex of the visual cone is located, but his geometry suggests that it must reside somewhere behind the eye (although I suspect he simply left this feature undetermined).

[548] For a biography of Galen, including the dates of his treatises, see Mattern 2013.

[549] Gal. *De plac. Hipp. et. Plat.* 7.4.3-4, 7.5.37-39 mentions *On Demonstration*, while *De usu part.* 10.6 K. 785-786 mentions *On Vision* [οἱ ὀπτικοί λόγοι].

in many ways he represents the inheritor of all the optical traditions that we have dealt with so far, philosophical, anatomical and geometrical. In addition, he also adopts technologies as cognitive tools in almost all the ways that I have identified with ealier scientific theorists, and he thus functions as a type of methodological successor as well. That being said, he presents an extreme consequence of this cognitive habit, letting both geometrical and material technologies infiltrate his physical models. For Aristotle and Euclid, geometrical diagrams provided a visible heuristic to conceptualize *hypothetical* entities, presenting a material instantiation of a visual ray that could not be seen, but only inferred. For Ptolemy, the geometrically determined bronze plate supplied him with an almost literal template on which to base the operative features of the *indeterminate* interior of the eye, which could be seen, but not in the way that his theoretical account required. For Galen, however, material and geometrical technologies combine and cause him to re-conceptualize anatomical features that he can actually *see* and has, in fact, already described in great detail. He re-shapes the messy, blood and curved optical nerves as clean, straight lines, ascribing them a physiological function that depends on their complete transition into geometrical entities. In other words, his geometrical heuristic takes epistemological dominance over his own known and catalogued observations.

As we shall see, there is yet another layer to Galen's adoption of technological heuristics: he draws a secondary conclusion about the function of his geometrical anatomy that cannot be supported by mathematical arguments alone. Instead, it rests on an unmentioned assumption that the triangular geometry of the optical nerves serves the same purpose in the body as triangular building levels, known as *libella*, do in construction. Galen uses geometry to understand the eye and uses material tools to understand his geometry. He uses a layered heuristic, but one that works across ontological realms. In this way, Galen represents an instance of a single theorist using almost all the heuristic-types encountered so far. Thus, as the heir to both previous knowledge and ealier methodologies, he provides a fitting conclusion to my investigations.

Commentators have long acknowledged the conceptual debt that Galen owes to the Stoics, Plato and Aristotle;[550] yet, by incorporating aspects of reflection into his account, he appears to draw on Democritus and Alcmaeon's mirror-theories as well. In fact, even more than Ptolemy, Galen employs a syncretic approach to vision, adopting arguments from his predecessors wherever their ideas overlap with and support his own. Ultimately, however, Galen draws from so many different theories that he ends up contradicting himself,[551] but his basic account is nevertheless clear: vision does not occur by means of rays leaving the eye, or εἴδωλα entering it, but by means of a taut visual cone stretched out by the "psychic *pneuma*" [πνεῦμα ψυχικόν].[552] This theory resembles

---

[550] Galen himself cites both Empedocles (*De plac. Hipp. et Plat.* 7.543; 7.6.11) and Plato (*De plac. Hipp. et Plat.* 7.6.1-22) as predecessors who promote ideas similar to his own, although commentators acknowledge Stoic *pneuma*-theory as Galen's chief influence. In contrast, Cherniss 1933 and Seigel 1970a: 46 emphasize the influence of Aristotle, while Seigel adds that Galen's account can subsume a modified Epicurean *eidola*-theory—but this may be stretching the volume of syncretism that one theory can coherently handle before bursting; cf. Hahm 1978: 90-91, n. 26. Wade 1998: 13 argues that Galen owes a conceptual debt to Ptolemy, although there are many reasons why this influence seems unlikely; see below.

[551] Seigel 1970a: 48 points out that while discrepancies sometimes occur between texts, Galen wrote his two main commentaries, *De usu part.* and *De Plac. Hipp. et Plat.*, around the same time, which largely precludes the possibility that inconsistencies arise because Galen's theory of vision changed over time.

[552] The Stoics grant an incredibly significant role to *pneuma* in their physics, making it both the binding agent that suffuses all matter, as well as the active force behind all movement. A. Long 1974: 152-158 examines *pneuma* more generally within Stoic physics, emphasizing that it is not simply a material substance, but something that is also capable of rational action. Although Galen is clearly indebted to the Stoics for many of his ideas about *pneuma*, it was a tremendously contested concept within Greek philosophy, especially as regards to its role in cognition and sensation; cf. section 1.2 above.

the Stoics' in many fundamental ways.[553] By comparison, Chrysippus states something quite similar, arguing that sight occurs insofar as visual *pneuma* moves from the heart and reaches the pupil, where it strikes, or "pricks" the external air. By the force of its blow, *pneuma* stretches the air into a tensed cone. As Aëtius reports:

> Χρύσιππος κατὰ συνέντασιν τοῦ μεταξὺ ἀέρος ὁρᾶν ἡμᾶς, νυγέντος μὲν ὑπὸ τοῦ ὀπτικοῦ πνεύματος, ὅπερ ἀπὸ τοῦ ἡγεμονικοῦ μέχρι τῆς κόρης διήκει, κατὰ δὲ τὴν πρὸς τὸν περικείμενον ἀέρα ἐπιβολὴν ἐντείνοντος αὐτὸν κωνοειδῶς, ὅταν ᾖ ὁμογενὴς ὁ ἀήρ. προχέονται δ' ἐκ τῆς ὄψεως ἀκτῖνες πύριναι, οὐχὶ μέλαιναι καὶ ὁμιχλώδεις· διόπερ ὁρατὸν εἶναι τὸ σκότος.
>
> Chrysippus says we see by virtue of the stretching of the intervening air. This air is pricked by the visual *pneuma*, which advances from the *hegemonikon* to the pupil. Upon its impact against the surrounding air the visual *pneuma* stretches the air conically wherever the air is homogeneous. Fiery rays, not black misty ones, are poured forth from sight. Hence darkness is visible (Aët. 4.15.3 = *SVF* 866; Aët. 4.15.2 = *SVF* 869).[554]

---

[553] Although we lack the Stoics' own texts about vision, we can more or less reconstruct their theory from later reports. It may be more appropriate, however, to talk about Stoic visual *theories*, since there was internal disagreement among the Stoics themselves. For the purposes of this chapter, I will take Chrysippus' account of visual perception as representative of the general Stoic position—not only because he adopts what could be considered the orthodox account, but also because Galen uses Chrysippus' theory as the primary counterpoint to his own. Dufour 2004 collects all the fragments of Chrysippus and the relevant evidence; cf. Tieleman 2003 and Gould 1970 (esp. 14-17) for a survey of scholarly accounts evaluating Chrysippus' contribution to Stoic thought.

[554] It is unclear whether Chrysippus proposed a quasi-extramissionist theory, or whether the *pneuma* simply stopped as soon as it reached the boundary of the eye and simply transferred its motion or power to the external air. Alexander of Aphrodisias, for instance, describes air being 'pricked' at the pupil, and gives no indication that any *pneuma* leaves the eye.

> εἰσὶν δέ τινες, οἳ διὰ τῆς τοῦ ἀέρος συνεντάσεως τὸ ὁρᾶν φασι γίνεσθαι. νυττόμενον γὰρ ὑπὸ τῆς ὄψεως τὸν συνάπτοντα τῇ κόρῃ ἀέρα σχηματίζεσθαι εἰς κῶνον.
> There are some that say that seeing happens because of the stretching of the air; for the air touching the pupil [of the eye] is pricked by sight and shaped into a cone (Alex. Aphr. *Mantissa* 130.14-17 = *SVF* 864).

Similarly, Diog. Laert. 7.157 = *SVF* 867 mentions only "the stretching of the light between sight and object into a cone" [τοῦ μεταξὺ τῆς ὁράσεως καὶ τοῦ ὑποκειμένου φωτὸς ἐντεινομένου κωνοειδῶς]; cf. Diog. Laert. 7.84 = Apollod. fr. 12. On the one hand, these passages make it seem likely that Chrysippus established no crucial role for *pneuma* exiting the pupil. On the other hand, the passage from Aëtius quoted above mentions "fiery rays" leaving the eye. This may in fact be another way of speaking about the luminous, visual *pneuma* and indicate that Chrysippus conceived of at least *some* substance leaving the eye, even if it did not itself travel all the way to the visible object. Indeed, both Geminus and Calcidius present passages that suggest something similar, although neither of them name Chrysippus as the Stoic personality whom they are discussing. Gemin. *Frag*. *Opt*. 24.11-12 states that "the intervening air is stretched and moves *along with* a light-like *pneuma*" [συνεκτείνεται ἤ συμφέρεται ὁ μεταξὺ ἀὴρ τῷ τῆς ὄψεως

While vision occurs when the visual *pneuma* reaches the air, it does not have the strength to produce a taut visual cone on its own. Rather, sufficient visual tension requires that the external air already be illuminated, suffused with light and thus "homogeneous" [ὁμογενής] to the visual *pneuma* (which, as Geminus reports, is particularly "luminous" or "light-like" [αὐγοειδής]).[555] When these conditions obtain and the visual cone is formed, the eye senses any objects entering the visual field and impinging upon it. As Diogenes Laertius reports, "the thing being seen is reported back as though through a walking-stick of stretched air" [ὡς διὰ βακτηρίας οὖν τοῦ ταθέντος ἀέρος τὸ βλεπόμενον ἀναγγέλλεσθαι].[556] Chrysippus calls the simultaneous two-way process "tensile motion" [ἡ τονικὴ κίνησις], whereby the eye's tension proceeds outward, while the image-transfer is relayed back to the eye.[557]

Galen's account involves many of the same commitments, although he insists upon differentiating himself from Chrysippus by arguing that the visual *pneuma* does not

---

αὐγοειδεῖ πνεύματι], while Calch. *In Tim.* 237 = *SVF* 2.863 mentions that vision "pours out" of the eye by means of the "stretching" [*intentione*] of the innate pneuma, which proceeds from the interior of the pupil. In general, the confusion seems to stem from the fact that according to Stoic physics both the interior of the eye and the external air are infused with connate *pneuma*. Thus, while it seems more coherent that Chrysippus did not advocate any *pneuma* leaving the eye, it is possible that he himself did not make a careful distinction.

[555] Gemin. *Frag. Opt.* 24.11-12.

[556] Diog. Laert. 7.157 = *SVF* 867; cf. Alex. Aphr. *Mantissa* 130.14-17 = *SVF* 864. However simple it seems, the walking-stick [βακτηρία] comparison is slightly difficult to parse. Although Chrysippus mentions only a walking-*stick* in the singular, it seems more likely that he does not mean this literally and instead imagines that the entire visual cone is filled with numerous such 'sticks,' which would together form a conical, continuous whole. Ultimately, then, as befits the Stoics' belief that only corporeal objects can act upon each other, Chrysippus would ultimately consider visual perception to be a type of touch; Cf. *SVF* 864; 851; cf. A. Long 1974: 153.

[557] *SVF* 864.

simply meet a homogenous substance, but actually assimilates the intervening air into its own nature:[558]

> οὕτως γοῦν εἰκός ἐστι καὶ τὸ παραγινόμενον εἰς ὀφθαλοὺς πνεῦμα κατὰ μὲν τὴν πρώτην ἔμπτωσιν ἑνοῦσθαι τε τῷ περιέχοντι καὶ συναλλοιοῦν αὐτὸ πρὸς τὴν ἰδιότητα τῆς ἑαυτοῦ φύσεως, οὐ μὴν ἐπὶ πλεῖστόν γ᾽ἐκτείνεσθαι.
>
> Thus, it is likely that in this way the *pneuma* in the eyes is united at the first impact with the surrounding air and that *pneuma* alters the air to its own proper nature, but does not itself stretch out to the furthest distance (Gal. *De plac. Hipp. et Plat.* 7.4.25).

Just like Chrysippus, Galen argues that visual *pneuma* causes a tense visual cone that has its apex in the eye and its base on the objects perceived. Yet, he rejects Chrysippus' analogy with a "walking-stick" [βακτήρια] and instead relies on a comparison with the sun, suggesting that just as sunlight illuminates and thus transforms air instantaneously without sending or receiving any material substance, the visual *pneuma* likewise alters the continuum of the surrounding air, thereby imbuing it with the sensate power to discern objects.[559] As such, the external air becomes a quasi-organ of sight, a virtual extension of the optical nerve, and, by extension, the brain. As he states:

> καὶ γίγνεται δὲ τοιοῦτον ὄργανον αὐτῷ πρὸς τὴν τῶν αἰσθητῶν οἰκείαν διάγνωσιν οἷον ἐγκεφάλῳ τὸ νεῦρον, ὥσθ' ὃν ἔχει λόγον ἐγκέφαλος πρὸς τὸ νεῦρον, τοιοῦτον ὀφθαλμὸς ἔχει πρὸς τὸν ἀέρα.
>
> And [the air] becomes [for the eye] the same kind of instrument for the proper discrimination of its sense objects, as the nerve is for the brain; therefore, as the brain is to the nerve, so too is the eye to the air. (Gal. *De plac. Hipp. et Plat.* 7.5.31-32).[560]

---

[558] Cf. Gal. *De plac. Hipp. et Plat.* 7.5.41.

[559] Gal. *De plac. Hipp. et Plat.* 7.5.5-8; 7.7.19; cf. *De usu part.* 3.10 K. 3.243.

[560] It is somewhat unclear whether Galen imagines that any *pneuma* actually leaves the eye during this transfer. On the one hand, he asserts that the *pneuma* "does not stretch out to the furthest distance" [οὐ μὴν ἐπὶ πλεῖστόν γ᾽ἐκτείνεσθαι], which could mean either that it actually stops at the "first impact" [ἡ πρώτη ἔμπτωσις] with the external air or that it extends a small distance from the eye. On the other hand, at *De plac. Hipp. et Plat.* 7.4.18, Galen claims that "for lions, leopards and other animals who have eyes that are

Because the air is now sensate, Galen, like Aristotle, argues that the intermediate air simply undergoes an instantaneous, "qualitative alteration" [ἀλλοίωσις][561] whenever an object impinges upon it.[562] That is, whenever a colour enters the visual field we simply perceive the resulting alteration down the length of the visual cone as though it were a nerve in our body.

Although this is the physical model of vision *outside* of the eye, Galen provides a highly detailed physiological account of each aspect *inside* the body as well. He begins from when we breathe air into our lungs, where it undergoes its first alteration or "elaboration" [κατεργασία].[563] The inhaled air then moves *via* the pulmonary vein into the heart, where it is further refined into vital *pneuma*, which travels through the arteries. Some of this *pneuma* travels upwards *via* the carotid arteries to the *retiform plexus* [τὸ δικτυοειδὲς πλέγμα], a net-like cluster of overlapping vessel at the base of the brain (this organ is now called the *retiform mirabile*). Here it is further elaborated into psychic

---

sufficiently luminous, it is possible for you to see at night, whenever they turn their pupil towards their nose, that a small circle of light appears on it" [λέουσι δὲ καὶ παρδάλεσι καὶ τῶν ἄλλων ζῴων οἷς αὐγοειδής ἐστιν ἱκανῶς ὁ ὀφθαλμός, ἔνεστί σοι θεάσασθαι νύκτωρ, ὅταν ἐπιστρέψωσι τὴν κόρην ἐπὶ τὴν ῥῖνα, κύκλον αὐγῆς ἐπ' αὐτῆς φαινόμενον]. That is, he seems to indicate that the luminous psychic *pneuma* actually exits the eye in the form of a cone and casts its brilliance on nearby objects, however faintly; cf. Seigel 1970a: 78-80.

[561] Although the term ἀλλοίωσις is Aristotelian in origin, Chrysippus also uses it, distinguishing himself from Zeno and Cleanthes, who still employ the concept of an "imprint" [τύπωσις] to conceptualize perception; cf. *SVF* 1.58 = Sext. Emp. *Ad math.* 7.230; *SVF* 2.56 = Sext. Emp. *Ad math.* 7.227-30; 7.372-373; cf. Hankinson 2003: 62.

[562] While I have here mentioned objects impinging on the visual cone, Galen, like Aristotle and Ptolemy, considers the primary object of vision to be colour; cf. *De usu part.* 8.6 K. 3.639-641.

[563] In many senses, *pneuma* forms the core of Galen's physiology, since it is responsible for both voluntary motion and sensation; cf. Rocca 2003: 59-66, who presents an account of Galen's general pneumatic physiology; cf. Temkin 1951.

pneuma.[564] Psychic *pneuma* moves from here into the brain's ventricles (the thalamus in particular), to which the optic nerves are attached. In fact, it is not entirely correct to say that the optic nerves are 'attached' to the thalamus, since for Galen the optic nerves are actually extensions of the brain itself.[565] These tripartite nerves stretch to the eyeballs (compressing slightly in order to fit through the ocular bone),[566] where they deliver the psychic *pneuma* responsible for vision.

As befits a careful anatomist, Galen outlines very intricate structures within the eyes as well. His ocular anatomy contains more or less the same labels as our modern structures, including the retina, the vitreous fluid, the iris, the cornea, etc. Nevertheless, while the names remain similar, Galen's assumptions about how these parts function differ substantially from our own. To begin with, he asserts that when the optic nerves reach the back of the eye, they widen to become the eye's three outer membranes: 1) the *sclera* (the white covering that protects the eye from the bone of the ocular socket); 2) the choroid membrane (which contains the arteries and veins that provide nutriment to the

---

[564] Cf. Gal. *De plac. Hipp. et Plat.* 7.3.23-29; 7.1.392; *De usu part.* 8.10 K. 3.663-664; 16.12 K. 333-334; *De anat. admin.* 14.5, 198 Duckworth. Herophilus seems to have been the first to describe the *retiform plexus* [δικτυοειδὲς πλέγμα] (cf. Heroph. T 121 von Staden), as well as the *choroid plexuses* [χοροειδῆ πλέγματα] (cf. Heroph. T 124, 125 von Staden), which Galen considers another organ that contributes to the elaboration of psychic *pneuma* in the brain; cf. Rocca 2003: 201-237 for a full account of this process. Yet, as Rocca 2002 points out the *retiform plexus* does not exist in either human or ape brains and is instead a feature of the ox brains on which Galen (and apparently Herophilus) primarily relied for cerebral anatomy; cf. *Anat. Admin.* K. 2.708; cf. Rocca 2003, esp. 36, 69-76, 202-208; Woollam 1958: 14.

[565] These nerves are composed of three parts: 1) a protective membrane called the *sclera* that stems from the *dura mater* covering of the brain; 2) a choroid tunic containing veins and arteries, which extends from both the *pia mater* and the choroid membrane; and 3) soft, encephalon-like sensory nerve tissue inside; cf. Gal. *De usu part.* 10.2 K. 3.762-764; cf. *De plac. Hipp. et Plat.* 7.3.4-5. At *De plac. Hipp. et Plat.* 7.5.18, however, Galen mentions only two main parts of the optic nerves: an inner, softer part similar to the brain, and an outer, harder part for protection. In addition, Galen asserts that one can discern that the optical nerves are hollow and possess a perforation down their centre (which makes them vessels perfectly crafted to carry the substantial amount of visual *pneuma* that vision requires); cf. Gal. *De plac. Hipp. et Plat.* 7.3-4, 7.5.20; *De usu part.* 16.3 K. 4.273-274; *Anat. Admin.* 14 K 2.170. Galen claims that many anatomists, including Herophilus and Eudemus call these nerves channels; cf. *Sympt. Caus.* 1.2 K. 7.88-89; *De libr. prop.* 3 K. 19.30; *De usu part.* 10.12 K. 3.813; cf. May 1968: 25, 29.

[566] Gal. *De usu part.* 10.1 K. 3.760.

cornea and iris);[567] and 3) the *retiform plexus*—which we now call the retina (which surrounds the transparent internal humours of the eye).[568] While we now hold the retina to be the photosensitive interior membrane of the eye and responsible for the perception of light stimulae, Galen assigns it a rather different function, proposing that it simply transmits the visual *pneuma* along its ridge-like structures, delivering *pneuma* to the primary organ of sight, the *crystalline*, ice-like humour [κρυσταλλοειδής] (what we now call the lens).[569]

Since Galen has already proposed a theory whereby the external air is turned into a sensate extension of the brain, it seems unnecessary to provide any further visual mechanism. Nevertheless, he describes a second aspect of the process, stating that when the psychic *pneuma* from the optic nerve reaches the crystalline humour, the transparent humour itself becomes sensate [αἰσθητική], capable of detecting the qualitative changes in the external visual cone.[570] On the one hand, Galen ascribes this primary role to the crystalline humour because of his close anatomical observations and experimentations (i.e. he notes that cataracts occur in the area in front of the humour, and thus prevent it from accurately assessing the qualitative change in the visual cone).[571] On the other hand, he relies on the same basic argument that Alcmaeon made, namely, that the crystalline

[567] It is named after the vessel-filled placenta, the χόριον.

[568] This is an additional *retiform plexus* to the one mentioned above. These ocular parts are extensions of the optical nerve; cf. n. 564 above.

[569] Gal. *De usu part.* 10.1 K. 3.760. Behind this crystalline humour is another transparent liquid, called the vitreous, or "glass-like" humour [ὑαλοειδῆς], which fills the majority of the eye. Galen also mentions that it is called the "lentiform" humour, but since eyeglass lenses had not yet been invented, this label did not carry the same implications in antiquity as today. Perhaps contrary to the expectations that have been built so far, Galen assigns no particular role to the glass-like fluid aside from supplying nutrients to the main organ of vision in front of it.

[570] Gal. *De plac. Hipp. et Plat.* 7.5.26.

[571] Gal. *De usu part.* 10.1 K. 3.760.

humour sees “by being white, bright, gleaming and pure” [λευκῷ καὶ λαμπρῷ καὶ στίλβοντι καὶ καθαρῷ].[572] At other times, however, Galen adopts vocabulary in line with Aristotle, calling the crystalline humour transparent and thus “light-like” or “luminous” [αὐγοειδές].[573] That being said, even though the crystalline humour is sensate, Galen holds that actual visual perception does not occur in the eye; rather, it takes place in the brain where the psychic *pneuma* of the ἡγεμονικόν ultimately registers this alteration.[574] Therefore, while the visual *pneuma* must extend *to* the crystalline humour, it must also transmit visual perceptions *back* to the psychic *pneuma* of the brain *via* the optics nerves. Galen remains agnostic as to whether this process involves *pneuma* actually flowing to and fro, or whether (as he deems more likely) a qualitative change occurs in the *pneuma* that already fills the nerves, which would then transfer the image instantaneously. Galen calls this an “alteration in a continuous substance” [ἡ κατὰ ποιότητα τῶν συνεχῶν ἀλλοίωσις].[575] Regardless of which option he endorses, both scenarios attribute a primary role to the *pneuma*-infused crystalline humour, and he provides a comprehensive anatomical model to support this.

I have been so thorough with Galen’s account up until now—even while leaving out a considerable number of details—in order to provide a glimpse at how

[572] Gal. *De usu part.* 10.1 K. 3.761.

[573] Gal. *De plac. Hipp. et Plat.* 7.7.1 This humour is altered by the colours that impinge upon the visual cone by virtue of its pure transparency. In other word, by being sensitized by the *pneuma* that reaches it *via* the passageways in the retina, the crystalline humour registers any qualitative change in the visual cone by undergoing a qualitative alteration itself. As Aristotle before him, Galen suggests than the smooth, clear and bright qualities of the crystalline humour allow it to undergo such an alteration instantaneously.

[574] Gal. *De plac. Hipp. et Plat.* 7.6.31.

[575] Gal. *De plac. Hipp. et Plat.* 7.4.1. Nevertheless, Galen also speaks elsewhere about the *pneuma* “flowing” and “moving” with the nerves (cf. *De plac. Hipp. et Plat.* 7.4.4), which conflicts somewhat with the idea that *pneuma* only transmits qualities, and does not itself move mechanically in the processes of motion and sensation.

comprehensively Galen describes ocular anatomy and how carefully he outlines the physiology of perception. Although previous thinkers, most notably Herophilus and Erasistratus, had already investigated the structures of the eye, Galen presents a thorough justification for each and every part, noting its role in the process of vision. This includes the eyelids, the muscles controlling them and tear ducts behind them. Recognizing this diligence will underline just how surprising it is when Galen stops his investigation in book 10 of *On the Usefulness of the Parts* in order to change course:

> σχεδὸν ἅπανθ’ ἡμῖν εἴρηται τὰ κατὰ τοὺς ὀφθαλμοὺς πλὴν ἑνός, ὃ προὐθέμην μὲν παραλιπεῖν, ὅπως μὴ δυσχεραίνοιτο τοῖς πολλοῖς ἥ τ’ ἀσάφεια τῶν λόγων καὶ τὸ μῆκος τῆς πραγματείας. ἐπεὶ γὰρ ἐχρῆν ἅψασθαι κατ’ αὐτὸ θεωρίας γραμμικῆς, ἧς οὐ μόνον ἀμαθεῖς εἰσιν οἱ πολλοὶ τῶν πεπαιδεῦσθαι προσποιουμένων, ἀλλὰ καὶ τοὺς ἐπισταμένους ἐκτρέπονταί τε καὶ δυσχεραίνουσι, διὰ τοῦτ’ ἄμεινον ἔδοξεν εἶναί μοι παντάπασιν αὐτὸ παραλιπεῖν. ἐνύπνιον δέ τι μεταξὺ μεμψάμενον, ὡς εἰς μὲν τὸ θειότατον ὄργανον ἀδικοῖμι, περὶ δὲ τὸν δημιουργὸν ἀσεβοῖμι παραλιπὼν ἀνεξήγητον ἔργον μέγα τῆς εἰς τὰ ζῷα προνοίας αὐτοῦ, προὔτρεψεν ἀναλαβόντα με τὸ παραλελειμμένον ἐπὶ τῇ τελευτῇ τοῦ λόγου προσθεῖναι.
>
> Nearly everything has been said on the subject of eyes except one thing, which I planned to leave out, lest the obscurity of the arguments and the length of the subject annoy the masses. For since it required touching upon theoretical geometry—which not only are many of those pretending to have been educated actually ignorant about, but those knowing it also avoid it and dislike it—it seemed best to me to leave it out entirely. But in the interim a dream censured me on the grounds that I was wronging the most godlike instrument, and was being impious towards the demiurge by having left unexplained a great work of his foresight in animals, and so I returned and took up once again what had been omitted and added it to the end of my account (Gal. *De usu part.* 10.12 K. 3.474).

We may consider Galen’s concession to the divine craftsman a mere conceit, allowing him to show off some of his geometrical training. Nevertheless, even if this is the case, he designates geometry as a particularly powerful tool—the “most godlike instrument” [τὸ θειότατον ὄργανον]—with which the divine demiurge constructs the human body. Yet, although Galen mentions visual rays when discussing the rectilinearity of sight, his primary divine, geometrical instrument is not the ray-line, as one might suspect, but a triangular plane.

The geometrical sections of *On the Usefulness of the Parts* mainly concern one anatomical feature: the optical chiasma. That is, before the optic nerves reach the eyes, they form what appears to be an 'x' (or the Greek letter 'χ'). Galen insists that the nerves do not actually *cross*; rather, they simply join together before splitting back apart and continuing on to their respective eyes. Since *On the Usefulness of the Parts* as a whole presents a teleological account for why it was both necessary and optimal for the divine demiurge to construct all the body parts exactly as he did, Galen needs to provide a physiological justifications for this feature. On the one hand, he argues that it allows for the transfer of *pneuma* from one nerve to the other in case of injury or blockage (or to increase the visual acuity of one eye if the other is closed.[576] On the other hand, the divine demiurge could have accomplished the same function simply by joining the two optic nerves in the brain.[577] Why, then, does the chiasma take the precise form that it does?

Galen solution is that by virtue of its geometry the chiasma guarantees that both eyes remain fixed on the same horizontal plane, thereby preventing double vision:

[576] Gal. *De plac. Hipp. et Plat.* 7.4.11-17; *De usu part.* 10.14 K. 3.831-838. Galen asserts that we can see the effects of this transfer when we shut an eye: he insists that this causes the pupil of the other eyes to dilate, which he explains as the iris inflating to accommodate the extra *pneuma* and thus pulling slightly outward as it expands (we can think of a flat inner tube being blown up, potentially causing its inner diameter to increase); cf. Gal. *De plac. Hipp. et Plat.* 7.4.15.

[577] Gal. *De usu part.* 10.12 K. 3.813-814. Galen suggests that connecting the vessels in the brain itself would also provide a mechanism by which the images from each eye could be collected in a single place, although he acknowledges that it is the ἡγεμονικόν that ultimately unifies the data from multiple organs into a single perception.

ἡμεῖς δ’ οὖν ἐπιθῶμεν ἤδη τῷ λόγῳ κεφαλὴν ἀναμνήσαντες, ὡς ἀναγκαῖόν ἐστι τοὺς ἄξονας τῶν ὀπτικῶν κώνων ἐν ἑνὶ καὶ ταὐτῷ τὴν θέσιν ἴσχειν ἐπιπέδῳ πρὸς τὸ μὴ διπλοῦν φαίνεσθαι τὸ ἕν. οἱ δὲ δὴ ἄξονες ἡμῖν οὗτοι τὴν ἀρχὴν ἔχουσι τοὺς ἐξ ἐγκεφάλου πόρους. ἐχρῆν οὖν ἔτι κυουμένου τε καὶ διαπλαττομένου τοῦ ζῴου κατὰ μιᾶς ἐπιπέδου τινὸς ἐπιφανείας αὐτοὺς τετάχθαι…τί οὖν τοῦτ’ ἔστι τὸ ῥᾷστόν τε καὶ πρόχειρον, ὅπερ ἐξ ἀρχῆς λέγειν προὔκειτο; τὸ συμβάλλειν ἀλλήλοις τοὺς πόρους. δύο γὰρ εὐθεῖαι γραμμαὶ συντυγχάνουσαι κατά τινα κοινὴν στιγμὴν οἷον κορυφὴν αὐτῶν ἐν ἑνὶ πάντως εἰσὶν ἐπιπέδῳ, κἂν εἰ τύχοιεν ἐντεῦθεν εἰς ἄπειρόν τι μῆκος ἐφ’ ἑκάτερα τὰ μέρη προσεκβαλλόμεναι. καὶ αἱ ταύτας δὲ τὰς δύο εὐθείας τὰς ἐκβαλλομένας ἐφ’ ὁσονοῦν ἐπιζευγνύουσαι καθ’ ὁντινοῦν τόπον εὐθεῖαι ταὐτὸν ἐπίπεδον ἴσχουσι ταῖς δύο τῷ καὶ πᾶν τρίγωνον ἐν ἑνὶ πάντως ὑπάρχειν ἐπιπέδῳ…τὴν μὲν οὖν ἀπόδειξιν παρ’ Εὐκλείδου μανθάνειν· μαθὼν δ’ αὖθις ἐπανήκειν ὡς ἡμᾶς, καί σοι δείξομεν ἐπὶ τοῦ ζῴου τὰς δύο ταύτας εὐθείας τοὺς ἐξ ἐγκεφάλου πόρους. ὧν ἑκάτερος εἰς τὸν καθ’ ἑαυτὸν ὀφθαλμὸν αὖθις, ὡς εἴρηται πρόσθεν, ἀμφιβλήστρου δίκην ἑλίττεται κυκλοτερῶς ἄχρι τοῦ κρυσταλλοειδοῦς ὑγροῦ περιλαμβάνων ἔνδοθεν αὐτοῦ τὸ ὑαλοειδές, ὡς ἐπὶ μιᾶς εὐθείας εἶναι τὴν κόρην καὶ τὴν ῥίζαν ὅλην τοῦ ὀφθαλμοῦ, καθ’ ἣν τὸ νεῦρον ἄρχεται λύεσθαι. καὶ τρίτον ἐπὶ τοῖσδε τὴν ἐν τοῖς πρόσω μέρεσι τοῦ ἐγκεφάλου συμβολὴν τῶν ὀπτικῶν νεύρων, ἀφ’ ἧς ἀρξάμενα προέρχεσθαι δι’ ἑνὸς ἐπιπέδου τούς θ’ ὅλους ὀφθαλμοὺς ἐγέννησεν ἐν δικαίᾳ θέσει καὶ τῶν ἐν αὐτοῖς κορῶν οὐδετέραν ὑψηλοτέραν ἀπέφηνε. διὰ ταῦτα μὲν δὴ βέλτιον ἦν ἐξ ἀρχῆς μιᾶς ὁρμᾶσθαι τὰ τὴν ὀπτικὴν αἴσθησιν τοῖς ὀφθαλμοῖς παρέξοντα νεῦρα.

And so let me place a cap on this account, having reminded you that the axes of the visual cones must be located on one and the same plane for a single object not to appear double. And indeed, these axes of ours have their beginning in the channels from the brain. And so it was necessary while the animal was still being grown and moulded that they were fixed on a single plane…and so what is this easy and ready-at-hand device, which I have been planning from the beginning to explain? It is the channels connecting with one another. For two straight lines joining together at a common point (operating as their apex) are entirely on a single plane, even if their sides should extend from there, away from one another, into a limitless distance. And if these two lines are extended to any distance, straight lines connecting them at any point will be on the same plane as these two, since each triangle lies entirely on a single plane…And so learn this proof from Euclid, and, having learned it, come back to us again, and I will prove to you that in an animal *the channels from the brain are these two straight lines*. Each of these reaches their respective eye, as has been mentioned earlier, and curves around it, just like a net, up as far as the crystalline humour, surrounding its vitreous

> humour inside it, so that the pupil is in a straight line with the whole root of the eye where the nerve begins to spread. And third, in addition to these things, the meeting of the optical nerves in the front part of the brain, from which they start to extend, generate the whole eyes on a single plane in the correct place and neither of their pupils appears higher. For these reasons, it was certainly better that the nerves providing visual perception to the eyes proceeded from a single source (Gal. *De usu part.* 10.13 K. 3.828-831, emphasis mine).

There are two ways to interpret the geometry that Galen has laid out. First, visual "axes" could extend from the encephalon, strike the back of the eyeball at its centre point and continue along the same unbroken path through the pupil (fig. 25):

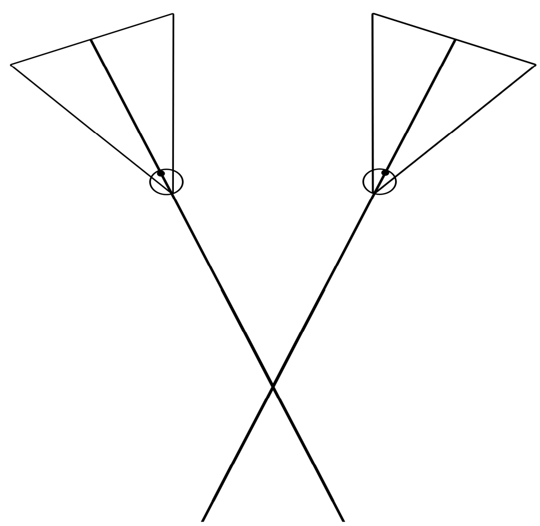

Fig. 25 Galen's Optic Chiasma (Version A)

In this case, the pupils would need to be located obliquely on the sides of the eyeballs, not directly at the front (see fig. 25). Second, the straight lines of the optic nerves could strike the back of both eyes at their centre points (their so-called roots), where they would deposit visual *pneuma* in the retiform plexus. In turn, a second line (this time a visual ray) would align the root to the pupil along its central axis (fig. 26):

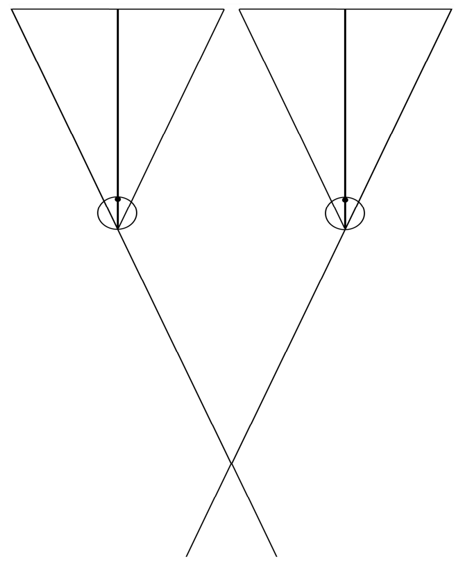

Fig. 26 Galen's Optic Chiasma (Version B)

While the first of these two options would present an even more extreme example of a geometrical reconfiguration of human physiology, insofar as it would relocate the pupils, the second seems more probable.[578] Regardless, Galen constructs his account in order to include triangular planar axes as key *anatomical* features—so much so that the optic nerves themselves have become lines. In fact, for the geometry to function, the nerves must not only be perfectly straight (although they are not), but they must also cross, which Galen has explicitly denied. The clean lines of Galen's geometry sterilize the bloody, slightly curved optical nerves into a perfect, useful and comprehensible body part. He has made flesh lines and lines flesh. His geometrical account has led him to constitute physical features that he has described in great detail, not simply hypothetical

[578] Seigel 1970b promotes the first view, and does not even consider the second possibility. In fact, he believes that Galen has radically altered his original *pneuma*-theory in order to present what is ultimately a ray theory. According to Seigel's account, light rays would need to proceed along a linear path through both the transparent humours of the eye and straight through the optical nerves. Since this would mean that we would only ever see the two separate points directly in line with these two axes, Seigel's reading is unconvincing. Yet, even this reading presents a geometrical reconfiguration of the ocular anatomy already established, since it would require the pupils to be much wider to accomodate the visual cone starting from the back of the eye.

entities that he cannot actually see.[579] He interprets the anatomy in front of him according to his geometrical heuristic.

5.5 Galen's Triangular Axes and Double Vision

A looming question remains for Galen's explanation of the optical chiasma: even if both eyes are on the same plane, how does this prevent double vision? To answer this, we need to look more closely at his geometrical optics, which differs from Euclid's in several significant aspects. For instance, whereas Euclid simply posits the rectilinear propagation of sight, Galen attempts to demonstrate this feature by using a thought experiment:

> ἔστω δή τις κύκλος ὁρώμενος ὑπὸ θατέρου τῶν ὀφθαλμῶν ἔτι θατέρου συγκεκλειμένου—κύκλον δὲ δηλον ότι καλῶ τὸ ἐκ μέσου πάντη ἴσον—ἀπὸ δὲ τῆς μέσης ταύτης στιγμῆς τῆς κατὰ τὸν κύκλον, ἣ δὴ καὶ κέντρον αὐτοῦ καλεῖται, μέχρι τῆς ὁρώσης αὐτὴν κόρης ὁδὸς εὐθεῖά σοι νοείσθω μηδαμόσε παρεγκλίνουσα μηδ' ἐκτρεπομένη τῆς κατ' εὐθὺ τάσεως, ἀλλ' ὥσπερ εἰ καὶ τρίχα λεπτὴν ἢ ἀράχνην ἀκριβῶς διατεταμένην ἀπὸ τῆς κόρης ἐπὶ τὸ κέντρον τοῦ κύκλου νοήσαις, οὕτω καὶ τὴν εὐθεῖαν γραμμὴν ἐκείνην. ἐπινόει δή μοι πάλιν ἀπὸ τῆς κόρης ἐπὶ τὴν περιορίζουσαν τὸν κύκλον γραμμήν, ἣν δὴ καὶ περιφέρειαν αὐτοῦ καλοῦσιν, ἄλλας εὐθείας γραμμὰς παμπόλλας ὥσπερ ἀράχνας τινὰς λεπτὰς ἐφεξῆς ἀλλήλων ἐκτεταμένας, καὶ τὸ μὲν ὑπὸ τῶν εὐθειῶν τούτων ἁπασῶν καὶ τοῦ κύκλου περιοριζόμενον σχῆμα κῶνον ὀνόμαζε, κορυφὴν δ' αὐτοῦ νόει τὴν κόρην καὶ βάσιν τὸν κύκλον. τὴν δ' ἀπὸ τῆς κόρης ἐπὶ τὸ κέντρον τοῦ κύκλου τεταμένην εὐθεῖαν ἁπασῶν τε τῶν ἄλλων εὐθειῶν καὶ παντὸς τοῦ κώνου μέσην ὑπάρχουσαν ἄξονα κάλει.
>
> Let there be a circle, seen by one of the eyes while the other is closed (and it is clear that I call a circle that which is equidistant from its mid-point in all directions), and from this mid-point of the circle (which is indeed also called its centre) consider a straight path right up to the pupil of the eye

[579] It could be that Galen is not transforming the optical nerves directly into lines, but that he is already 'thinking with' an anatomical illustration. I say this because it would be easier to assume that the optical nerves are straight while looking at a two-dimensional depiction, since they would only need to accomplish this with respect to a single axis, not both horizontally and vertically. This would constitute another level of technological mediation, this time through anatomical drawing techniques.

> that sees it, neither bending nor curving from its straight extension in any way; rather, think of the straight line in the same way as a thin hair or cobweb carefully stretched from the pupil to the centre of the circle. Conceive again of other many other straight lines extending from the pupil in succession to the line circumscribing the circle, which they also call its circumference, just as though thin cobwebs, and call the shape circumscribed by all these straight lines and the circle a cone; and conceive of the pupil as its apex and the circle as its base. And call the straight line extending from the pupil to the centre of the circle (the one that holds the middle position with respect to all the lines and the entire cone) its axis (Gal. *De usu part.* 10.12 K. 3.815-816).

Galen's model is somewhat of a hybrid, insofar as his "cobwebs" provide a physical description of the rectilinearity of sight for an audience (supposedly) unfamiliar with visual rays, while the circle that forms the cone's base is geometrical abstraction, with a strict definition provided.[580]

More than justifying his geometry in his own unique way, Galen establishes an optics that differs from both Euclid's and Ptolemy's in another key aspect: instead of using the language of visual *angles*, Galen talks about magnitudes occupying space in the visual field. In his formulation, one object taking up the same space as another will appear "over against" it, and as a corollary he includes something never asserted by Euclid: objects never appear alone in isolation; they always appear accompanied by something else in the visual field.[581] He illustrates these aspects in a geometrical proposition (fig. 27):

[580] To further aid in comprehension, Galen provides an additional experimental detail, stating that we should imagine a single millet seed interposed between the pupil and the centre point of the circle, placed somewhere along the axis. Galen notes that even this tiny seed would prevent us from seeing the centre point, while if the seed were to be removed, the centre would again be visible (Gal. *De usu part.* 10.12 K. 3.816). This appears to be a reformulation of Aristotle's explanation of why visual acuity can fail to perceive something tiny, such as a millet seed; cf. Arist. *Sens.* 445b31-446a1.

[581] Gal. *De usu part.* 10.12 K. 3.818.

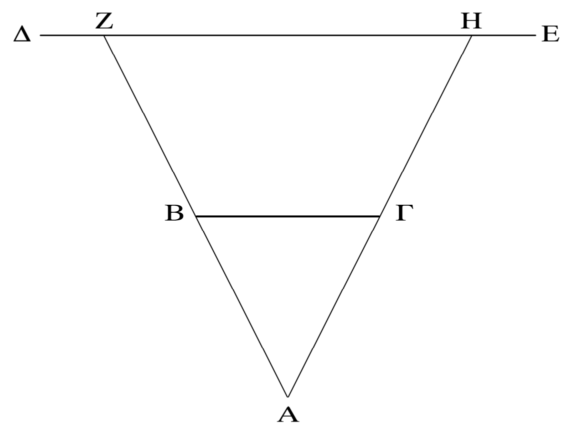

Fig. 27 Galen's Optics (*De usu part*. 10.12)

νοείσθω γὰρ κόρη μὲν ἡ πρὸς τὸ α. τὸ δ' ὁρώμενον μέγεθος ἔστω βγ, καὶ προσπιπτέτωσαν ὄψεις ἀπὸ τῆς α κόρης πρὸς ἑκάτερα τῶν βγ. κείσθω δ' ἐπέκεινα τοῦ βγ μέγεθος τὸ δε, καὶ προσεκβεβλήσθωσαν αἱ αβ, αγ ὄψεις, καὶ προσπιπτέτωσαν τῷ δε κατὰ τὸ ζη. δῆλον οὖν, ὡς τὸ βγ μέγεθος ὁραθήσεται κατὰ τὸ ζη. καὶ διὰ τοῦτ' ἀποκρυφθήσεται μέν, ὡς μηδ' ὅλως ὁρᾶσθαι, τὸ ζη. τὰ δ' ἑκατέρωθεν αὐτοῦ μεγέθη, τό τε δζ καὶ τὸ ηε, παρὰ τὸ βγ φανεῖται βλεπόμενα, καὶ μέντοι καὶ αὐτὸ τὸ βγ καθ' ἕτερον τρόπον ἐροῦμεν βλέπεσθαι παρ' ἐκείνων ἑκάτερον.

Conceive of the pupil at α. Let the visible magnitude be βγ. Let visual rays from the pupil, α, extend to each of the points β and γ. And let some magnitude δε lie beyond βγ, and let the visual rays αβ and αγ be produced and extend to the magnitude δε at ζ and η. And so, it is clear that the magnitude βγ will be seen over against ζη. And because of this, ζη will be hidden, so as not to be seen at all; yet, the magnitudes on either side of this, δζ and ηε, will appear to be seen alongside βγ; and moreover, we shall say that βγ is seen beside each of them in each place (Gal. *De usu part.* 10.12 K. 3.820-821).

As simple as this assertion sounds, a considerable geometrical consequence follows: since objects appear in the visual field only insofar as they occupy a portion of it, all objects must be represented as magnitudes apprehended by at least two hypothetical visual rays. In other words, Galen cannot coherently represent a visible object as a single point with a single visual ray extending to it. Instead, he must represents any object with a triangle.

This formulation impacts his account and experience of double vision. Since Galen cannot treat *diplopia* as the failure of two visual rays to align on a single object—since an object cannot be represented by a single point—he does not explain double vision as the failure of two hypothetical visual axes to align. Instead, he construes it as the disjunction of his two triangular visual planes (fig. 28):

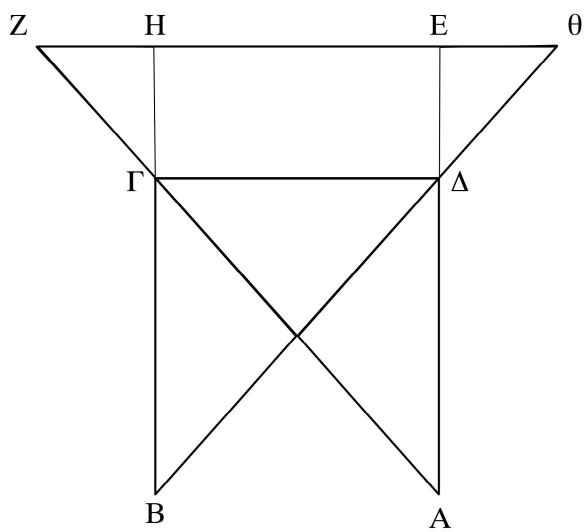

Fig. 28 Galen's Mechanism of Spatial Perception (*De usu part.* 10.12)

ὁ δὲ περὶ τοῦ δευτέρου τοῦ μὴ κατὰ τὸν αὐτὸν τόπον μήτε τῷ ἑτέρῳ τῶν ὀφθαλμῶν πρὸς τὸν ἕτερον μήτ' ἀμφοῖν ἅμα πρὸς τὸν ἕτερον βλέπεσθαι τὸ βλεπόμενον, ἀλλ' ἐν ἄλλῳ μὲν ὑπὸ τοῦ δεξιοῦ, ἐν ἄλλῳ δ' ὑπὸ τοῦ ἀριστεροῦ, ἐν ἄλλῳ δ' ὑπ' ἀμφοῖν, ὃ μέλλω νῦν ἐρεῖν ἐστιν. ἔστω γὰρ ἡ μὲν δεξιὰ κόρη πρὸς τὸ α, ἡ δ' ἀριστερὰ πρὸς τὸ β. τὸ δ' ὁρώμενον μέγεθος ἔστω τὸ γδ, καὶ προσπιπτέτωσαν ὄψεις ἀφ' ἑκατέρας τῶν κορῶν πρὸς τὰ γδ καὶ προσπεσοῦσαι προσεκβεβλήσθωσαν. ὁραθήσεται δὴ τὸ γδ μέγεθος ὑπὸ μὲν τῆς δεξιᾶς κόρης κατ' εὐθὺτοῦ εζ μεγέθους, ὑπὸ δὲ τῆς ἀριστερᾶς κατ' εὐθὺ τοῦ ηθ, ὑπὸ δ' ἀμφοτέρων ὁμοῦ κατ' εὐθὺ τοῦ ηε. ὥστ' οὔθ' ἡ ἑτέρα τῇ ἑτέρᾳ οὔθ' ἅμα ἀμφότεραι τῇ ἑτέρᾳ κατὰ τὸν αὐτὸν ὄψονται τόπον τὸ ὁρώμενον.

Concerning the second proposition: no object is seen in the same place by one eye as it is by the other; nor is it seen by both eyes together in the same place as either individually; instead, an object is seen in one place by the right eye, in another by the left, and in still another by both eyes; this is

> what I now intend to say: let the right pupil be at α, the left at β. Let the visible magnitude be γδ and let visual rays from each pupil extend to γ and δ, and having been extended, let them be drawn further. The magnitude γδ will be seen by the right pupil directly over against the magnitude εζ, while by the left pupil it will be seen directly over against the magnitude ηθ, but by both entirely straight in front of ηε. Thus, neither pupil will see the object in the same place as the other, and both together will not see it where either sees it individually (Gal. *De usu part.* 10.12 K. 3.821-822).

Galen here asserts that although each eye will see a magnitude in a different spot, they will collectively form a common image over against that length that both magnitudes hide. In other words, we determine location by the superposition of an object in both visual fields—or, as Galen states, "when both eyes look together, [an object] will seem to hold the middle location as compared to when each eye produces an image of the object separately" [ἀμφοτέροις δ᾽ἅμα θεωμένοις τὴν μέσην χώραν ἐπέχειν δοκεῖ τῆς ἑκατέρων καταμόνας φαντοζομένης].[582] Although this may seem a relatively trivial change from Ptolemy's mechanism of binocular spatial perception, Galen's explanation has a very curious consequence: it causes him to deny the possibility of horizontal double vision. Since every object falls *somewhere* in each visual field, wherever the visual axes are pointed, Galen suggests that they will always average out their differences. In other words, regardless of where each eye perceives an object individually, it will always be perceived at the midpoint between the two eyes. Thus, for Galen, horizontal double vision simply never happens.

As far as I can tell, Galen is the first person to make this argument. This claim becomes even more extraordinary when we recall that while using his ruler, Ptolemy construed *all* double vision as something occurring across a horizontal plane. Because of

[582] Gal. *De usu part.* 10.12 K. 3.824.

his particular mechanism, Ptolemy did not even mention the possibility that vertical double vision could occur. Thus, by using a different technology to investigate vision, and placing great epistemological weight on the diagrams that he has drawn (and the triangular visual planes that they depict), Galen reconfigures the concept of double vision in a completely different way. Yet, something even more interesting happens when he seeks experimental confirmation.

> ἐναργὲς δὲ τεκμήριον τοῦ λεγομένου λάβοις ἄν, εἰ τὸ παρατεθλιμμένου θατέρου τῶν ὀφθαλμῶν διπλοῦν ψευδῶς φαινόμενον ἐπιμύσας θατέρῳ θεάσασθαι βούλοιο. μία μὲν γὰρ τελέως ἀποτελεῖται φαντασία τῆς τοῦ βλεπομένου θέσεως, ἣν εἶχεν ὁ κεκλεισμένος νῦν ὀφθαλμός, ὅτ' ἀνέῳκτο· ἡ λοιπὴ δ' ἀμετάπτωτος μένει τὴν ἐξ ἀρχῆς φυλάττουσα χώραν…διὰ τοῦτο δὲ καὶ οὐ πᾶσα διαστροφὴ τῆς κόρης διττὸν ποιεῖ φαντάζεσθαι τὸ βλεπόμενον, ἀλλ' ἥτις ἂν αὐτὴν ὑψηλοτέραν ἢ ταπεινοτέραν ἐργάζηται τοῦ κατὰ φύσιν. αἱ δὲ πρὸς τὸν μέγαν κανθὸν ἢ πρὸς τὸν μικρὸν παραγωγαὶ μᾶλλον μὲν ἀριστερὸν ἢ δεξιὸν ἀποφαίνουσι τὸ βλεπόμενον, οὐ μὴν διττόν γ' ἐργάζονται· μένουσι γὰρ ἐφ' ἑνὸς ἐπιπέδου τῶν κώνων οἱ ἄξονες.
>
> Have clear proof of what is being asserted: if you wish to see an object appear falsely doubled, press one of the eyes to the side and look, and then close it and look with the other. For one image of the object's location will be lost entirely (the one that the now-closed eye had), but the other remains unaltered, preserving the position it held from the beginning)…For this reason, not every displacement of the pupil makes the visible object appear double, but only a displacement that makes it higher or lower than its natural position. Those displacements moving it sideways towards the large or small corner of the eye make the object appear to the left or right, but they do not make it appear double; for the axes of the cones remain on a single plane (Gal. *De usu part.* 10.12 K. 3.825-826).

According to Galen, his experiment confirms his geometrical argument. He asserts that horizontal displacement of one pupil will merely cause the image seen by them both to slide to the left or right; it will not cause the image to split into two.

Although it is problematic to rely on 'what actually happens' as an epistemological touchstone,[583] when I myself conduct Galen's experiment, I cannot reproduce his results. Instead, when I (very gently) push one of my eyes, I produce both visual displacement and double vision. This occurs whether I manually move my eyes to the left and right (which produces horizontally oriented *diplopia*), or up and down (which produces vertically oriented *diplopia*). Galen places so much weight on his geometrical model, however, that he extends his conclusions to deny that either cross-eyed or 'wall-eyed patients see double, so long as their eyes are vertically aligned:

> καὶ ὅσοι γε διεστράφησαν τοὺς ὀφθαλμοὺς ἢ ὕστερον ἢ εὐθέως κατ' ἀρχὰς ἐν τῇ κυήσει, μηδετέρας μὲν κόρης ὑψηλοτέρας γενομένης, ἀλλὰ τῷ προσαχθῆναι τῇ ῥινὶ τὸν ἕτερον ὀφθαλμὸν ἢ ἀπαχθῆναι βλαβέντες, οὐδὲν ἐν τῇ τῶν ὁρωμένων διαγνώσει πλημμελοῦσιν. οἷς δ' ἐπὶ τὸ ταπεινότερον ἢ ὑψηλότερον μετήχθη, πάνδεινα πάσχουσιν ἐκστρεφόμενοί τε καὶ καθιστάντες εἰς ἴσον αὐτάς, ἵν' ἀκριβῶς θεάσωνται.
>
> And all those who have had their eyes displaced either early on or right at the beginning of their generation, if neither pupil is made higher, but they have been distored either in being directed toward or away from the nose, they will not hit a false note in recognizing the things being seen. But if [their eyes] are altered either lower or higher, they suffer terrible things, both in turning and setting them equal so that they might see accurately (Gal. *De usu part.* 10.12 K. 3.826-827).

Despite Galen's assertions, any cross-eyed or wall-eyed person can confirm that double vision is indeed possible across a horizontal plane. In short, Galen denies the existence of a certain visual phenomenon that we take as somewhat common, no other ancient opticial theorist rejected and Ptolemy previously confirmed. From these examples, we can see how a slight shift in the diagrammatic entities will actually change what will be conceptualized as an optical phenomenon. That is, these entities shape how Galen perceives and interprets his own visual experiences.

[583] See Lehoux 2012 for an examination of this difficulty with respect to ancient science.

5.6 Galen's *Libella*

Along with some interesting epistemological questions, Galen's account raises a few geometrical questions as well. To begin with, how does ensuring that both eyes are on the same plane also ensure that one eye is not higher than the other? What if the eyes are simply tilted in the head? Why does Galen think that a triangular plane guarantees that the eyes are level in this way? To my mind, Galen has adopted this triangular geometry because of an iconic piece of technology: the builder's level, also called the διαβήτης or *libella*. Galen uses the geometrical diagram as a heuristic through which to think about anatomy and its function, while also implicitly using a material implement as a heuristic through which to think about the application of that geometry. By examining how this technological artifact operates in tandem with Galen's geometrical account, I can end my examination by returning to see how humble, every-day tools can shape ancient physical theories even in the midst of more complex technological environment of experimentation.

Carpenter's squares have been used in the Mediterranean since at least the eleventh century BCE and are one of the oldest construction tools.[584] They are simple in design, composed of two equal-length boards that meet at a perfect right angle, with a third board securing them in place. The three pieces form a right-angled isosceles triangle that can be used to measure corners, ensure rectilinearity, etc. A small extension of the two equal sides and the addition of a hanging plumb line transform this tool into a mechanism for adjudicating levelness, the *libella* (fig. 29):

[584] Cuomo 2007: 84; she cites the fact that a carpenter's square was found in the tomb of Sennedjem, an Egyptian architect of the twentieth dynasty (1340-1084 BCE).

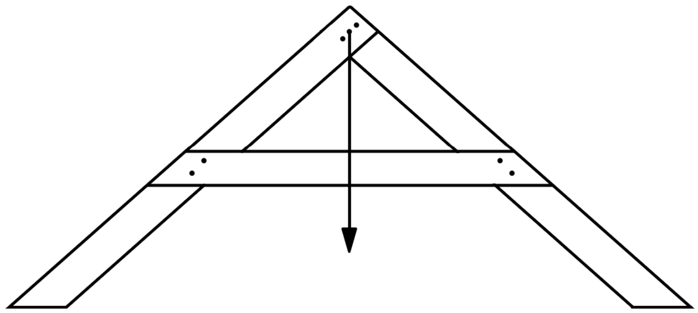

Fig. 29 A *Libella*

Place the legs on a given surface, and if the plumb line hangs straight down over the centre mark, the surface is level. This simple tool must have been used widely, since during the second century CE, it became one of principle icons of builders and carpenters, appearing with increasing frequency on burial tombs, where it acted both as a totem of their trade and a symbol for the 'leveling' that death enforces.[585] Thus, in Galen's time, the *libella* would have been one of the most recognizable emblems of construction, and its use in ensuring surfaces were horizontal would have been widely known.

Although Galen's chiasma lacks a plumb line and is situated horizontally, not vertically, I nevertheless find it probable that the triangular *libella* is behind Galen's physiological assumptions for two reasons. First, he treats the optical chiasma as though its functional feature were its triangularity, making the connection [ἡ συμβολή] of the two optical chiasmas a third point related to the backs of the two eyes. To be sure, Galen justifies his geometry by quoting Euclid's *Elements*: "If two straight lines intersect one another, they are on a single plane, and every triangle is on a single plane" [ἐὰν δύο εὐθεῖαι τέμνωσιν ἀλλήλας, ἐν ἑνί εἰσιν ἐπιπέδῳ, καὶ πᾶν τρίγωνον ἐν ἑνί ἐστιν

[585] Cuomo 2007: 77-102.

ἐπιπέδῳ].[586] As such, the mention of triangles could simply be an artifact of Euclid's definition. Still, there is a second reason for understanding the *libella* as a hidden technological heuristic: Galen frames the chiasma as a device [μηχανή] nature used as she constructed [δημιουργῆσαι] the body:

> καὶ οὐ τοῦτό φημι νῦν, ὡς οὐκ ἂν ἐξεῦρέ τινα μηχανὴν ἡ φύσις τῆς τε γενέσεως αὐτοῦ καὶ τῆς θέσεως, ὡς μήτε βλάπτειν τι τῶν παρακειμένων μήτε βλάπτεσθαι, εἴπερ ὅλως ἀναγκαῖον ἦν αὐτὸ δημιουργῆσαι, καὶ μὴ δι' ἑτέρου ῥᾴστου τε καὶ προχείρου τὴν ἐν ἑνὶ τῶν δύο πόρων ἐπιπέδῳ θέσιν ἐκπορίσασθαι δυνατὸν ἦν.
>
> And I deny this now, that nature would not have found some *device* of generation and placement so that she neither harmed any of the anatomical features around it, nor was [this feature] harmed by them, if it was entirely necessary to have constructed this, and it was not possible to contrive the placement of the two passageways on a single plane through another easy and ready-at-hand means (Gal. *De usu part.* 10.13 K. 3.829).

Understanding Galen's geometry not as an abstract endeavour, but as a practical one, fits well with his image of the divine craftsman using mathematics as a 'divine tool' to build the body. He seems to be envisioning nature with a pencil behind her ear and a *libella* in her hand, using mathematics to practical ends (much in the same way that Galen himself uses his geometrical training). In this way, one cognitive tool would help determine the application of another, as the target field of explanation becomes further mediated by a layered technological heuristic—in this case an unexpressed one.

This particular case study can shed a great deal of light into the process of theory-formation in ancient science, in part because prior to his geometrical account, Galen already has a physiological explanation for the optical chiasma. Although he questions, prods and interrogates his first answer, I would suggest that he does not this do not out of unrestrained curiosity or an unrelenting commitment to the truth. Rather, he is concerned

[586] Gal. *De usu part.* 10.13 K. 3.831; cf. Eucl. *Elem.* 11, 2.

about the chiasma's shape because he has a geometrical solution in hand. Of course, this geometry is in turn shaped by an implicit technological heuristic through which Galen interprets the consequences of his mathematics. He also layers technological heuristics on top of each other, even across ontological realms, as the lines on the page become lines in the body, and the lines in the body function like those used in the world.

5.7 Conclusion

Ptolemy contructs technological apparatuses to stablilize and investigate both monocular and binocular spatial perception, literally focusing our attention on certain visual behaviours. To this end, he first constructs a technology to stabilize the location of two objects within a single plane of sight. At the same time, he reads this device into the functional mechanism of vision, as the axis of the apparatus becomes the axis of his eyes. In other words, he himself constructs a technology to solve a certain *experimental* problem, only to then presume that nature has produced the same tool in our eye to solve an *experiential* problem. The case of the bronze plaque is less direct. Ptolemy does not construct this experimental apparatus to explain the mechanism of monocular spatial perception itself, but designs the plaque as a way to measure the angles of incidence and reflection. Nevertheless, he employs this technology as cognitive structure through which to explain monocular spatial perception. In so doing, he reads the geometry of the device into the operational features of the eye, making its geometrical centre the vertex of the visual cone.

Galen, in a similar fashion, employs geometrical technologies to interpret the anatomy of the ocular nerves, and in so doing, transforms the flexible and unstructured parts of the body into perfectly straight geometrical entities. Yet, he develops his model and draws mathematical conclusions that are not endogenous to his digrams but arise from unexpressed assumptions taken from the *libella*. Both of these authors use experiments and geometry to understand the behaviours of sight. But, when investigating vision with certain tools, they end up finding the tools themselves. The technologies that they look with become the technologies that they see.

CONCLUSION: TECHNOLOGY AND THE TOOL BOX

6.0 Looking Backwards and Forwards

As early as Empedocles, authors portrayed some version of a creator god who crafted natural beings as though an artisan using his tools. Thus, by considering how Galen uses the diving demiurge in his account of vision, we have in some sense returned to where we started. Indeed, just like his predecessors, Galen employs the concept of a technical nature in order to comprehend the incredible order displayed in the world, which he sees extending right down to the micro-structures of the eye. And, like Plato and Aristotle before him, he derives certain teleological commitments from this frame, constructing multiple biological arguments from design. Regardless of any common philosophical implications, however, it has become clear that calling nature "technical" means something different for Galen than for his predecessors. In fact, it takes on new meaning according to each separate technological environment. Empedocles, Democritus and Plato lived in a world of lamps, mirrors and cisterns, while Ptolemy and Galen inhabited an empire of infrastructure, implements and experimental apparatuses. The materials and devices that made up their respective surroundings produced distinct cognitive worlds. Thus, when these theorists wanted to explain some natural phenomenon, they simply had different conceptual tools at hand.

In many ways, recognizing the role that technology plays in theory-formation can provide one possible model for scientific development, insofar as technological improvements not only enable scientists to recognize new natural behaviours, but they also supply new cognitive tools on which to model the world. In this case, it would not necessarily be an intrinsic deficiency that causes a theory to be cast aside, but a newer, shinier device. In this light, we might ask whether Erasistratus' pressurized body really was a conceptual advance given all the manifold problems with it. Indeed, gravity-flow makes up a large part of how the arterial system actually works.[587] More than this, however, I have argued that cognitive worlds do not simply reflect a chronological accumulation of technological improvements; they can be fragmented. I have thus advocated for a far less homogeneous and linear understanding of how theory-formation works. Plato and Aristotle's accounts of respiration and the vascular system show that theorists can apply technological heuristics modally to explain different features of the same phenomenon at different times. Sometimes these heuristics work in tandem, and sometimes they conflict. In my investigation of vision, I extended this idea to show how Democritus employs layered heuristics, using one technology to interpret another and thereby superimposing the respective behaviours of mirrors and wax on top of each other. In all these instances, the technological heuristic mediates how the theorist experiences the world, suggesting which features of the phenomenon are important and which physical parts are instrumental. In this way, technologies adjust the operational definition of the target field of explantion.

Another common thread is found throughout all my investigations: the physical behaviours theorists derive from technological devices often belong to what we might consider incidental material aspects. In other words, theorists do not think simply with abstract versions of their implements, but with the particular devices in front of them. Euclid and the tradition of geometrical optics provides an example of this idea, insofar as

[587] For instance, blood in the veins does not return to the heart by cardiac propulsion. It rises because of the contraction of our muscles, and tiny valves prevent it from flowing back downwards.

the diagrams that articulate vision ostensibly represent abstract, immaterial relations, but he adopts the particular material features on the page as physical assumptions about the visual ray. The geometrical space of the diagram becomes the proper space of vision, only for the entities within that space to leap back out into the world. His physical rays thus operate with hybrid ontologies, simultaneously acting as an abstraction, a representation and the thing itself. In the last chapter, I showed how even experimental apparatuses can have this same affect, whereby the material devices used to interrogate vision get translated into geometrical entities, only to tranform again into the physiology of the eye. Thus, whether through analogies, images or experiments, technologies instruct and construct our understanding of natural phenomena.

In many ways, I have been describing a theory of cognition that takes material tools to be cognitive tools. Perhaps we have a box full of such tools, but they work in different, sometime opposed ways, and depending on what we are attempting to explain, we reach for one, then another, whenever we see fit. Most of the time, we automatically look for a cognitive tool that performs a task similar to that of the *explanandum*. For instance, if we need to imagine how one thing hits another, we reach for the hammer; if we need to imagine how one thing divides another, we reach for the knife. At the same time, as I have shown with Ptolemy and Galen, we also tend to utilize tools that happen to be in our hand already. For instance, Ptolemy builds an experimental apparatus that organizes his experience of vision, and, as a result, he develops a theory of the eye that resembles the technology in front of him. We might then consider whether we have a cognitive "tool box" after all, since this implies that we can grab an implement according to need. We may instead have something more akin to a cognitive Swiss army knife,[588] where it is difficult and somewhat cumbersome to look for every possible attachment. Instead, once we have the saw out, we might be inclined to open a bottle with it. We might even do so without much reflection. Yet, however accessible cognitive tools may be, when they are activated, they structure the way we experience and conceptualize the world. Thus, by paying close attention to how material devices affect physical assumptions, we can gain critical insight into how technology participates in theory-formation. In short, we can see how technologies can manufacture both theories and things.

[588] I owe this image to Henry Cowles.

WORKS CITED

Alfieri, V.E. 1936. *Gli Atomisti: frammenti e testimonianze.* Bari: Laterza.

Andersen, K. 1987. "Ancient Roots of Linear Perspective." In *From Ancient Omens to Statistical Mechanics: Essays on the Exact Sciences Presented to Asger Aaboe*, eds. J.L. Berggren and B.R. Goldstein. Copenhagen: University Library, pp. 75-89.

Asper, M. 2009. "The two cultures of mathematics in ancient Greece." In *The Oxford Handbook of the History of Mathematics*, eds. E. Robson and J. Stedall. New York: Oxford University Press, pp. 107-132.

Avotins, I. 1980. "Alexander of Aphrodisias on Vision in the Atomists." *Classical Quarterly* 30, no. 2: 429-454.

Balansard, A. 1997. Technè *dans les* Dialogues *de Platon*. PhD diss., Univ. de Paris X-Nanterre; publ. as 2001. *Technè dans les Dialogues de Platon*. *L'empreinte de la sophistique*. Sankt Augustin: Academia Verlag.

Baldes, R. 1975. "Democritus' Theory of Perception: Two Theories or One?" *Phronesis* 2: 93-105.

_____ 1976. "Theophrastus' Witness to Democritus on Perception." *Apeiron* 10, no. 1: 42-48.

____ 1978. "Democritus on the Nature and Perception of 'Black' and 'White'." *Phronesis* 23, no. 2: 87-100.

Ball, P. 2001. *Bright Earth: The Invention of Colour*. London: Penguin.

Barnes, J., trans. 1975. *Aristotle*: *Posterior Analytics*. Oxford: Oxford University Press.

_____ 1982. *The Presocratic Philosophers*, 2 vols. (rev. ed.). New York: Routledge.

Beare, J. 1906. *Greek Theories of Elementary Cognition from Alcmaeon to Aristotle*. New York: Oxford University Press.

Bethe, E. 1964. *Buch und Bild im Altertum*. Amsterdam: Verlag Adolf M. Hakkert.

Berryman, S. 1997. "*Horror Vacui* in the Third Century BC: When is a Theory not a Theory?" In *Aristotle and After*, ed. R. Sorabji. Bulletin of the Institute of Classical Studies, suppl. 68, pp. 147-157.

_____ 1998. “Euclid and the Sceptic: A Paper on Vision, Doubt, Geometry, Light and Drunkenness.” *Phronesis* 43, no. 2: 176-196.

_____ 2009. *The Mechanical Hypothesis in Ancient Greek Natural Philosophy*. New York: Cambridge University Press.

Bicknell, P. J. 1968. “The seat of the mind in Democritus.” *Eranos* 66: 10-23.

_____ 1969. “Democritus’ theory of precognition.” *Revue des études greques* 82: 318-26.

Bijker, W., T.P. Hughes and T. J. Pinch, eds. 1987. *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*. Cambridge, Mass.: MIT Press.

Black, M. 1962. *Models and Metaphors: Studies in Language and Philosophy*. Ithaca: Cornell University Press.

Boll, H. 1894. “Studien über Claudius Ptolemäus.” *Jahrb. Class. Philol. Suppl.* 11: 53-66.

Booth, N.B. 1960. “Empedocles’ Account of Breathing.” *Journal of Hellenic Studies* 80: 10-15.

Boyer, C. 1946. “Aristotelian References to the Law of Reflection.” *Isis* 36: 92-95.

_____ 1959, repr. 1987. *The Rainbow: From Myth to Mathematics*. Princeton, New Jersey: Princeton University Press.

Broadie, S. 1993. “Aristotle’s perceptual realism.” *Southern Journal of Philosophy* 31, suppl.: 137-159.

Brownson, C.D. 1981. “Euclid’s Optics and its Compatibility with Linear Perspective.” *Archive for History of Exact Sciences* 24: 165-194.

Bruno, V. 1977. *Form and Color in Greek Painting*. New York: W.W. Norton & Company.

Brunschwig, J. 1983. “Aristote et le statut épistémologique de la théorie de l’arc-en-ciel.” In *Graceful Reason: Essays in Ancient and Medieval Philosophy Presented to Joseph Owens.* ed. Lloyd P. Gerson. Papers in Mediaeval Studies 4. Toronto: Pontifical Institute of Mediaeval Studies, pp. 115-134.

Bruun, C. 2000. “Water Legislation in the Ancient World (c. 2200 B.C.-C. A.D. 500): The Greek World.” In *Handbook of Ancient Water Technology*, ed. O. Wikander. Leiden: Brill, pp. 557-574.

Burkert, W. 1972. *Lore and Science in Ancient Pythagoreanism*, trans. E.L. Minar Jr. Cambridge, Mass.: Harvard University Press.

_____ 1977. “Air-Imprints or Eidola: Democritus’ Aetiology of Vision.” *ICS* 2: 97-109.

Burnet, J. 1920. *Early Greek Philosophy,* 3rd ed. London: A & C Black Ltd.

Burnett, D.G. 2005. *Descartes and the Hyperbolic Quest: Lens Making Machines and Their Significance in the Seventeenth Century*. Philadelphia: Transactions of the American Philosophical Society.

Burnyeat, M. 1992, repr. 1995a. “Is an Aristotelian Philosophy of Mind Still Credible? A Draft.” In *Essays on Aristotle’s* De Anima, eds. M.C. Nussbaum and A.O. Rorty. New York: Oxford University Press, pp. 15-26.

_____ 1993. “Aristote voit du rouge et entend un ‘do’: Combien se passe-t-il de choses? Remarques sur *De Anima*, II 7-8.” *Revue philosophique de la France et de l’étranger* 188: 263-280; trans. as 1995b “How Much Happens When Aristotle Sees Red and Hears Middle C? Remarks on *De Anima* 2. 7-8.” In *Essays on Aristotle’s* De Anima, eds. M.C. Nussbaum and A.O. Rorty. New York: Oxford University Press, pp. 421-434.

_____ 2001. “Aquinas on ‘Spiritual Change’ in Perception.” In *Ancient and Medieval Theories of Intentionality*, ed. D. Perler. Leiden: Brill, pp. 129-153.

_____ 2002. “*De Anima* II 5.” *Phronesis* 47: 28-90.

Calvo-Martínez, T. 2011. “The Aristotelian Conception of Imagination: *De anima* III 3, 427b14-428b10.” In *La psychologie d’ Aristote*, ed. Cristina Rossitto. Paris: Librairie philosophique J. Vrin, pp. 57-71.

Camardo, D. *et al.* 2011. “Toilets in the Urban and Domestic Water Infrastructure.” In *Roman Toilets: Their Archaeology and Cultural History*, eds. G.C.M. Jansen, A.O. Koloski-Ostrow and E. Moorman Leuven: Peeters, pp. 71-94.

Cappelle, W. 1912. “Das Proemium der Meteorologie.” *Hermes* 47: 514-35.

_____ 1935. “Meteorologie.” In *Paulys Realencyclopädie der classischen Altertumswissenschaft*, rev. G. Wissova, suppl. 6. Stuttgart, pp. 315-358.

Carra de Vaux, Baron 1902. *Le livre des appareils pneumatiques et des machines hydrauliques par Philon de Byzance, edité d'après les versions arabes d’ Oxford et de Constantinople et traduit en français par le Baron Carra de Vaux*. Paris.

Casadei, E. 1997. “La dottrina corpuscolare di Asclepiade e i suoi rapporti con la tradizione atomista.” *Elenchos* 18: 77-106.

Caston, V. 1985. *Empedocles’ Theory of Vision.* PhD diss., University of Texas at Austin.

_____ 1996. “Why Aristotle Needs Imagination.” *Phronesis* 41: 20-55.

_____ 1998. “Aristotle and the Problem of Intentionality.” *Philosophy and Phenomenological Research* 58: 249-298.

Cech, B. 2012. *Technik in der Antike.* Theiss: Beilefeld.

Charbonneaux, J. 1958. *Les bronzes grecs.* Paris: Présses Universitaires de France.

Charles, D. 2011. “Desire in Action: Aristotle’s Move.” In *Moral Psychology and Human Action in Aristotle*, eds. M. Pakaluk and G. Pearson. New York: Oxford University Press, pp. 76-94.

Cherniss, H. 1933. “Galen and Posidonius’ Theory of Vision.” *American Journal of Philology* 54: 154-61.

_____ 1935, repr. 1964. *Aristotle’s Criticism of Presocratic Philosophy.* New York: Octagon Books.

Cocchi, A. 1758. *Discorso primo sopra Asclepiade*. In R. M. Green, trans. 1955. *Asclepiades, His Life and Writings: A Translation of Cocchi's* Life of Asclepiades and *Gumpert's* Fragments of Asclepiades. New Haven, CT: Elizabeth Licht.

Congdon, L.O.K. 1981. *Caryatid Mirrors of Ancient Greece*. Mainz am Rhein: Philipp von Zabern.

Craik, E.M. 2006. *Two Hippocratic Treatises:* On Sight *and* On Anatomy. Boston: Brill.

Crouch, D.P. 1993. *Water Management in Ancient Greek Cities*. New York: Oxford University Press.

Cuomo, S. 2001. *Ancient Mathematics*. New York: Routledge.

_____ 2002. “The Machine and the City: Hero of Alexandria’s *Belopoeica*.” In *Science and Mathematics in Ancient Greek Culture*, eds. C.J. Tuplin and T.E. Rihll. New York: Oxford University Press, pp. 165-177.

_____ 2007. *Technology and Culture in Greek and Roman Antiquity*. New York: Cambridge University Press.

Dambska, I. 1971. "La Théorie de la science dans les oeuvres de Claude Ptolémée." *Organon* 8: 109-122.

De Grummond, N.T. 2007. *Corpus Speculorum Etruscorum: Great Britain 3*. Rome: L'Erma di Bretschneider.

De Lauretis, L. 1987. *Technologies of Gender: Essays on Theory, Film and Fiction*. Indianapolis: University of Indiana Press.

de Pace A. 1981. "Elementi Aristotelici nell' *Ottica* di Claudio Tolomeo." *Rivista critica di storia della filosofia* 36: 123-138.

Des Chenes, D. 2001. *Spirits and Clocks: Machine & Organism in Descartes*. Ithaca: Cornell University Press.

Dick, S. 2014. *After Math: Cognition, Computation, Collaboration and Proof in the Postwar United States*, PhD. diss., Harvard University.

Dicks, D.R. 1959. "Thales." *Classical Quarterly* 9, no. 2: 294-309

Diels, H. 1879. *Doxographi Graeci*. Berlin: G. Reimer.

_____ 1884. "Gorgias und Empedokles." *Sitzungberichte der preussischen Akademie*, pp. 343-368; repr. in Diels (1969) *Kleine Schriften zur Geschichte der antiken Philosophie*. Darmstadt: Wissenschaftliche Buchgesellschaft, pp. 159-184.

_____ 1893. "Über das physikalische System des Straton." *Sitzungsberichte der Prüssichen Akademie der Wissenschaften zu Berlin* 1: 101-127.

_____ 1924. *Antike Technik: Sieben Vorträge.* Teubner: Berlin.

Drabkin, I.E., ed. and trans. 1950. *Caelius Aurelianus: On Acute Diseases and on Chronic Diseases*. Chicago: University of Chicago Press.

Drachmann, A. G. 1932. *Ancient Oil Mills and Presses.* Copenhagen: B. Lumos.

_____ 1963. *The Mechanical Technology of Greek and Roman Antiquity*. Madison: The University of Wisconsin Press.

Dufour, R. 2004. *Chrysippe: Oeuvre philosophique, Tome I.* Paris: Les Belles Lettres.

Duhem, P. 1969. *To Save the Phenomena: An Essay on the Idea of Physical Theory from Plato to Galileo*, trans. E. Doland and C. Maschler. Chicago: University of Chicago Press.

Duminil, M.-P. 1983. *Le sang, les vaisseaux medical d'Eschyle et les écrits hippocratique.* Paris.

English, R.B. 1915. "Democritus' theory of sense perception." *Transactions and Proceedings of the American Philological Association* 46: 218-221.

Evans, J. 1998. *The History and Practice of Ancient Astronomy*. New York: Oxford University Press.

Everson, S. 1997. *Aristotle on Perception*. New York: Oxford University Press.

Fahlbusch, H. 1994. "Die Abschätzung der Leistungsfähigkeit der archaischen Wasserleitung Athens." In *Das archaische Wasserleitungsnetz für Athen und seine späteren Bauphasen*, ed. R. Tölle-Kastenbein. Mainz: Zabern, pp. 109-110.

Falcon, A. 2005. *Aristotle and the Science of Nature: Unity without Uniformity*. New York: Cambridge University Press.

Ferrini, d. M. F., ed. and trans. 1999. *i Colori*. Pisa: Edizioni ETS.

Finley, M. 1965. "Technological innovation and economic progress in the ancient world." *The Economic History Review* 18: 29-45.

_____ 1973, repr. 1999. *The Ancient Economy*. Berkeley: University of California Press.

Forbes, R.J. 1964-1972. *Studies in Ancient Technology*, 9 vols. Leiden: Brill.

Foucault, M. 1988. "Technologies of the Self." In *Technologies of the Self*, eds. L.H. Martin, H. Gutman and P.H. Hutton. Amherst: University of Massachusetts Press, pp. 16-49.

Fowler, D. 1987, 2nd ed. 1999. *The Mathematics of Plato's Academy*. New York: Oxford University Press.

Fraser, P.M. 1969. "The Career of Erasistratus of Ceos." *Rendiconti*, Classe di Lettere, Istituto Lombardo—Accademia di Scienze e Lettre 103: 518-537.

_____ 1972. *Ptolemaic Alexandria*. Oxford: Clarendon Press.

Frede, M. 2004. "Aristotle's Account of the Origins of Philosophy." *Rhizai* 1: 9-44.

Freeland, C. 1990. "Scientific Explanation and Emperical Data in Aristotle's *Meteorology*." *Oxford Studies in Ancient Philosophy* 8: 67-102.

Furley, D.J. 1957. "Empedocles and the Clepsydra." *Journal of Hellenic Studies* 77: 31-34.

Furley, D.J. and J.S. Wilkie. 1984. *Galen On Respiration and the Arteries*. Princeton: Princeton University Press.

Galison, P. 1997. *Image and Logic: A Material Culture of Microphysics*. Chicago: The University of Chicago Press.

Garani, M. 2007. *Empedocles Redivivus: Poetry and Analogy in Lucretius*. New York: Routledge.

Gentner, D. 1982. "Are Scientific Analogies Metaphors?" In *Metaphor: Problems and Perspectives*, ed. D.S. Miall. Brighton: Harvester Press.

Gentner, D. and C. Clement. 1988. "Evidence for relational selectivity in the interpretation of analogy and metaphor." In *The Psychology of Learning and Motivation: Advances in Research and Theory*, ed. G.H. Bower. New York: Academic Press, pp. 307-358.

Gentner D. and Jeziorski, M. 1989. "Historical Shifts of the Use of Analogy in Science." In *The Psychology of Science*, eds. B. Gholson *et al*. Cambridge: Cambridge University Press.

Gigerenzer, G. and R. Selten. 2001. "Rethinking Rationality." In *Bounded Rationality: The Adaptive Toolbox*. Cambridge, Mass.: MIT Press, pp. 1-12.

Ginouvès, R. 1962. *Balaneutikè: Recherches sur le bain dans l'antiquité grecque.* Paris: Bibliothèque des écoles françaises d'Athènes et de Rome.

Glaser, F. 2000a. "Fountains and Nymphaea." In *Handbook of Ancient Water Technology*, ed. O. Wikander. Boston: Brill, pp. 413-452.

_____ 2000b. "Water Landscaping." In *Handbook of Ancient Water Technology*, ed. O. Wikander. Boston: Brill, pp. 453-466.

Gottschalk, H.B. 1961. "The Authorship of Meteorologica, Book IV." *Classical Quarterly* 11, no. 1: 67-79.

_____ 1964a. "Strato of Lampsacus: some texts." *Proceedings of Leeds Philosophical and Literary Society* 11: 95-182.

_____ 1964b. "The De Coloribus and its Author." *Hermes* 92: 59-85.

_____ 1980. *Heraclides of Pontus*. New York: Oxford.

Gould, J.B. 1970. *The Philosophy of Chrysippus*. Leiden: Brill.

Govi, G. 1885. *L'Ottica di Claudio Tolomeo, da Eugenio, ammiraglio di Sicilia, scrittore del secolo XII, ridotta in latino sovra la traduzione arabe di un testo Greco imperfetto, ora per la prima volta, conforme a un codice della Bibliotecta Ambrosiana, per deliberazione della R. Accademia delle Scienze di Torino.* Torino.

Graham, D.W. 2013. *Science Before Socrates: Parmenides, Anaxagoras and the new Astronomy*. New York: Oxford University Press.

Green, K. 1994. "The Study of Roman Technology: some theoretical constraints." In *Theoretical Roman Archaeology: Proceedings of the first conference*, ed. E. Scott. Avebury: Aldershot, pp. 39-47.

_____ 2000. "Technological innovation and economic progress in the ancient world: M.I. Finley reconsidered." *Economic History Review* 53: 29-59.

_____ 2009. "Inventors, Invention, and Attitudes toward Innovation." In *Oxford Handbook of Engineering and Technology in the Classical World*, ed. J.P. Oleson. New York: Oxford University Press, pp. 800-818.

Gundert, B. 1992. "Parts and their Roles in Hippocratic Medicine." *Isis* 83: 453-465.

Guthrie, W.K.C. 1965. *A History of Greek Philosophy Vol. 2: The Presocratic Philosophers*. Cambridge: Cambridge University Press.

Hahm, D.E. 1978. "Early Hellenistic Theories of Vision and Perception of Color." *Studies in Perception: Interrelations in the History of Philosophy and Science*, eds. P.K. Machamer and R.G. Turnbull. Columbus, Ohio: Ohio State University Press, pp. 60-95.

Hall, J.J. 1983. "Was Rapid Scientific and Techical Progress Possible in Antiquity." *Apeiron* 17, no. 1: 1-13.

Hankinson, R.J. 2003. "Stoic Epistemology." In *The Cambridge Companion to the Stoics*, ed. B. Inwood. New York: Cambridge University Press, pp. 59-84.

Harig, G. 1983. "Die philosophischen Grundlagen des medizinischen Systems des Asklepiades von Bithynien." *Philologus* 127: 43-60.

Harris, C.R.S. 1973. *The Heart and Vascular System in Ancient Greek Medicine: from Alcmaeon to Galen*. Oxford: Oxford University Press.

Harry, B. 1970. "Epicurus: Some Problems in Physics and Perception." *Greece and Rome*, 17, no. 1: 58-63.

Haskins, C.H. 1924. *Studies in the History of Medieval Science*. Cambridge, Massachusetts: Harvard University Press.

Heath, Sir T. 1913, repr. 1981. *Aristarchus of Samos: The Ancient Copernicus*. New York: Dover.

_____ 1921, 2nd ed. 1981. *A History of Greek Mathematics*, 2 vols. New York: Dover.

_____ 1931, 2nd ed. 1963. *A Manual of Greek Mathematics*. New York: Dover.

_____ 1932, repr. 1991. *Greek Astronomy*. New York: Dover.

Heiberg, J.L. 1882. *Litterargeschichtliche Studien Über Euklid*. Leipzig: Teubner.

Hesse, M. 1966. *Models and Analogies in Science*, rev. ed. Notre Dame, Indiana: Notre Dame University Press.

Hodge, A.T. 1992, repr. 2002. *Roman Aqueducts & Water Supply*. London: Duckworth.

_____ 2000. "Aqueducts." In *Handbook of Ancient Water Technology*, ed. O. Wikander. Leiden: Brill, pp. 39-66.

Holmes, B. 2010. *Symptom and the Subject*. Princeton, New Jersey: Princeton University Press.

Hofstader, D. and E. Sander. 2013. *Surfaces and Essences: Analogy as the Fuel and Fire of Thinking*. New York: Basic Books.

Humphrey, J.W. 2006. *Ancient Technology*. Westport, Conn.: Greenwood Press.

Hultsch, F. 1899. "Winkelmessungen durch die Hipparchische Dioptra." *Abhandlungen zur Geschichte der Mathematik* 9: 193-209.

Ierodiakonou, K. 2005. "Empedocles on Colour and Colour Vision." *Oxford Studies in Ancient Philosophy* 29: 1-37.

Inwood, B. 1992. *The Poem of Empedocles*. Toronto: University of Toronto Press.

Irby-Massie, G.L. and P.T. Keyser. 2002. *Greek Science of the Hellenistic Era: A Sourcebook.* New York: Routledge.

Jamison, E. 1957. *Admiral Eugenius of Sicily: His Life and Work*. London: Oxford University Press.

Jansen, G.C.M. 2000. "Urban Water Transport and Distribution." In *Handbook of Ancient Water Technology*, ed. O. Wikander. Leiden: Brill, pp. Wikander, 103-126.

Johansen, T.K. 1997. *Aristotle on the Sense-Organs*. New York: Cambridge University Press.

Jones, A. 1986. *Pappus of Alexandria: Book 7 of the Collection*. New York: Springer.

_____ 1994. "Peripatetic and Euclidean Theories of the Visual Ray." *Physis* 31, no. 1: 47-76.

_____ 2007. "On Some Borrowed and Misunderstood Problems in Catoptrics." *Centaurus* 30, no. 1: 1-17.

Jouanna, J. 1999. *Hippocrates*, trans. M.B. DeBevoise. Baltimore: The Johns Hopkins University Press.

Katsoff, L. 1947. "Ptolemy's Scientific Method." *Isis* 38: 18-22.

Keller, E.F. 2002. *Making Sense of Life: Explaining Biological Development with Models, Metaphors, and Machines*. Cambridge, Mass.: Harvard University Press.

Keyser, P.T. and G.L. Irby-Massie. 2008. *The Encyclopedia of Ancient Natural Scientists: the Greek tradition and its many heirs*. New York: Routledge.

King, R.A.H. 2006. *Common to Body and Soul. Philosophical Approaches to Explaining Living Behaviour in Greco-Roman Antiquity*. Berlin: de Gruyter.

_____ 2009. *Aristotle and Plotinus on Memory*. New York: Walter de Gruyter.

_____ 2010. "Aristotle's *De memoria* and Plotinus on memory." In *Les Parva Naturalia: Fortune antique et médiévale*, eds. C. Grellard and P.-M. Morel. Paris: Publications de la Sorbonee, pp. 101-120.

Kleijn, G. de. 2001. *The Water Supply of Ancient Rome: City Area, Water, and Population*. Amsterdam: J.C. Gieben.

Knorr, W. 1975. *The Evolution of the Euclidean Elements: A Study of the Theory of Incommensurable Magnitudes and Its Significance for Early Greek Geometry*. Boston: D. Reidel.

_____ 1983. "The Geometry of Burning-Mirrors in Antiquity." *Isis* 74, no. 1: 53-73.

_____ 1985. "Archimedes and the Pseudo-Euclidean *Catoptrics*: Early Stages in the Ancient Geometric Theory of Mirrors." *Archives internationals d'histoire des sciences* 35: 27-105.

_____ 1986. *The Ancient Traditions of Geometric Problems*. Boston: Birkhäuser.

_____ 1991. "On the Principle of Linear Perspective in Euclid's 'Optica'," *Centaurus* 34: 193-210.

_____ 1992. "When Circles Don't Look Like Circles: An Optical Theorem in Euclid and Pappus." *Archive for History of Exact Sciences* 44: 287-329.

Koortbojian, M. 2013. "Review—Perspective in the Visual Culture of Classical Antiquity, Rocco Sinisgalli." *Classical Journal Online* 2013.05.06: 1-2.

Kranz, W. 1912. "Die Ältesten Farbenlehren der Griechen." *Hermes* 47: 126-140.

Kuhn, T. 1979. "Metaphor in Science." In *Metaphor and Thought*, ed. A. Ortony Cambridge: Cambridge University Press, pp. 409–19.

Laberrière, J.-L. 1984. "Imagination humaine et imagination animale chez Aristote." *Phronesis*: 29: 17-49.

_____ 2000. "Sentir le temps, regarder un tableau, Aristote et les images de la mémoire." In *Construction du temps dans le monde grec ancien*, ed. C. Darbo-Peschanski. Paris: CNRS Editions, pp. 269-286.

Lackenbacher, H. 1913. "Beiträge zur antiken Optik." *Wiener Studien* 35: 34-61.

Lakoff, G. and M. Johnson. 1980. *Metaphors We Live By*. Chicago: The University of Chicago Press.

Laird, W.R. and S. Roux, 2008. "Introduction." In *Mechanics and Natural Philosophy Before the Scientific Revolution*, eds. Laird, W.R. and S. Roux. Dordrecht: Springer, pp. 1-11.

Lamb, W. 1969. *Greek and Roman Bronzes*. New York: Lincoln MacVeagh.

Lammert, F. 1920. "Eine neue Quelle für die Philosophie der mittleren Stoa I." *Wiener Studien* 41: 113-121.

_____ 1920/21. "Eine neue Quelle für die Philosophie der mittleren Stoa II." *Wiener Studien* 42: 36-46.

Lehoux, D. 1999. "All Voids Great and Small, Being a Discussion of Place and Void in Strato of Lampsacus' Matter Theory'." *Apeiron* 32: 1-36.

_____ 2012. *What Did the Romans Know? An Inquiry into Science and Worldmaking*. Chicago: University of Chicago Press.

Leith, D. 2009. "The Qualitative Status of the *Onkoi* in Asclepiades' Theory of Matter." *Oxford Studies in Ancient Philosophy* 36: 283-320.

_____ 2012. "Pores and Void in Asclepiades' Physical Theory." *Phronesis* 57: 164-191.

LeJeune, A. 1947. "La dioptre d' Archimède." *Annales de la Sociétée scientifique de Bruxelles* 61: 27-47.

_____ 1948. *Euclide et Ptolémée: deux stades dans l'optique géométrique grecque*. Louvain: Bibliothèque de l'Université.

_____ 1956. *L'Optique de Claude Ptolémée dans la version latine d'après l'arabe de l'émir Eugène de Sicile.* Louvain: Bibliothèque de l'Université.

_____ 1957. *Recherches sur la catoptrique grecque.* Mémoires de l'Académie Royale de Belgiques: Classe des lettres et des sciences morales et politiques. 2nd series, vol. 52, fasc. 2. Brussels: Palais des Académies.

_____ 1989. *L'Optique de Claude Ptolémée*. New York: Brill.

Leunissen, M. 2010. *Explanation and Teleology in Aristotle's Science of Nature*. New York: Cambridge University Press.

Lewis, M.J.T. 1999. "Vitruvius and Greek aqueducts." *Papers of the British School at Rome* 67: 145-172.

_____ 2000a. "Theoretical Hydraulics, Automata, and Water Clocks." In *Handbook of Ancient Water Technology*, ed. O. Wikander. Leiden: Brill, pp. 343-370.

_____ 2000b. "The Hellenistic Period." In *Handbook of Ancient Water Technology*, ed. O. Wikander. Leiden: Brill, pp. 631-648.

_____ 2001. *Surveying Instruments of Greece and Rome*. New York: Cambridge University Press.

Lindberg, D. 1976. *Theories of Vision from Al-Kindi to Kepler*. Chicago: University of Chicago Press.

Lloyd, G.E.R. 1966. *Polarity and Analogy*. Cambridge: Cambridge University Press.

_____ 1970. *Early Greek Science: Thales to Aristotle*. London: Chatto & Windus.

_____ 1973. *Greek Science after Aristotle*. London: W.W. Norton & Co.

_____ 1975. "A note on Erasistratus of Cos." *Journal of Hellenic Studies* 95: 172-175.

_____ 1979. *Magic, Reason and Experience: Studies in the Origin and Development of Greek Science.* New York: Cambridge University Press.

_____ 1992. "Methods and Problems in the History of Ancient Science: The Greek Case." *Isis* 83, no. 4: 564-577.

_____ 1996. *Aristotelian Explorations*. New York: Cambridge University Press.

Long, A.A. 1966. "Thinking and Sense-Perception in Empedocles: Mysticism of Materialism?" *Classical Quarterly* 16: 256-76.

_____ 1974. *Hellenistic Philosophy: Stoics, Epicureans, Sceptics*. London: Duckworth.

Long, C. P. 2006. "Saving 'Ta Legomena': Aristotle and the History of Philosophy." *The Review of Metaphysics* 60, no. 2: 247-267.

Longrigg, J. 1967. "Roots." *Classical Review* 17, no. 1: 1-4

_____ 1976. "The 'Roots of All Things'." *Isis* 67, no. 3: 420-438.

_____ 1988. "Anatomy in Alexandria in the Third Century B.C." *The British Journal for the History of Science* 21, no. 4: 455-488.

_____ 1993. *Greek Rational Medicine: Philosophy and medicine from Alcmaeon to the Alexandrians*. New York: Routledge.

Lonie, I.M. 1964. "Erasistratus, the Erasistrateans, and Aristotle." *Bulletin of the History of Medicine* 38: 426-443.

_____ 1965. "Medical Theory in Heraclides of Pontus." *Mnemosyne* 18, 126-43.

_____ 1973. "The Paradoxical Text 'On the Heart'." *Medical History* 17: 1-15, 136-153.

_____ 1981. "Hippocrates the Iatromechanist." *Medical History* 25: 113-150.

Lorenz, H. 2007. "The Assimilation of Sense to Sense-Object in Aristotle." *Oxford Studies in Ancient Philosophy* 33: 179-220.

Lo Presti, R. 2008. *In forma di senso. L'encefalocentrismo del tratto ippocratico* Sulla malattia sacra *nel suo contesto epistemologico*. Aglaia 10. Rome: Carocci Editore.

Louis, P. 1982. *Aristote, Météorologiques*. Paris: Société d'Édition.

Lucore, S.K. and M. Trümper, eds. 2013. *Greek Baths and Bathing Culture: New Discoveries and Approaches*. Leuven/Paris: BABESCH.

Majno, G. 1975. *The Healing Hand: Man and Wound in the Ancient World*. Cambridge, Mass.: Harvard University Press.

Mackie, J.L. 1976. *Problems from Locke.* New York: Oxford University Press.

Mansfeld, J. 1990. "Doxography and Dialectic: the Sitz im Leben of the 'Placita'." *Aufstieg und Niedergang der römischen Welt* II: 36.4, eds. W. Haase and H. Temporini. New York: De Gruyter, pp. 3056-229.

Martin, Th. H. 1871. "Ptolémée, auteur de l'Optique…est-il le meme que Cl. Ptolémée, auteur de l'Almagest?" *Bullettino di bibliografia e di storia delle scienze matematiche e fisiche* 4: 466-469.

Marx, L. 2010. "Technology The Emergence of a Hazardous Concept." *Technology and Culture* 51, no. 3: 561-577; orig. publ. as 1997. "Technology The Emergence of a Hazardous Concept." *Social Research* 64: 965–88.

Mattern, S. 2013. *The Prince of Medicine: Galen in the Roman Empire*. New York: Oxford University Press.

May, M.T., trans. 1968. *Galen On the Usefulness of the Parts of the Body*, 2 vols. Ithaca, New York: Cornell University Press.

Meißner, B. 1999. *Die technologische Fachliteratur der Antike. Struktur, Überlieferung und Wirkung technischen Wissens in der Antike (ca. 400 v. Chr.-ca. 500n. Chr.).* Berlin: Akademie.

Merker, A. 2002. "Aristote et l'Arc-en-Ciel: Enjeux Philosophiques et Étude Scientifiques." *Archive for History of Exact Sciences* 56: 183-238.

Millerd, C. 1908. *On the Interpretation of Empedocles*. Chicago: Garland.

Mitcham, C. 1979. "Philosophy and the History of Technology." in *The History and Philosophy of Technology*, eds. G. Bugliarello and D.B. Doner. Urbana: University of Illinois Press, pp. 163-201.

Moritz, L.A. 1958. *Grain-Mills and Flour in Classical Antiquity*. Oxford: Clarendon.

Mugler, C. 1959. "Les theories de la vie at la conscience chez Démocrite." *Extr. de la Revue de philologie* 33: 7-38.

Murphy, D. 2005. “Aristotle on Why Plants Cannot Perceive.” *Oxford Studies in Ancient Philosophy* 29: 295-339.

Netz, R. 1999. *The Shaping of Deduction in Greek Mathematics*. New York: Cambridge University Press.

_____ 2004. “Eudemus of Rhodes, Hippocrates of Chios and the earliest form of a Greek mathematical text.” *Centaurus* 46: 243-286.

Neuburger, H.L. 1930. *The Technical Arts and Sciences of the Ancients.* New York: The MacMillan Company.

Neugebauer, O. 1975. *A History of Ancient Mathematical Astronomy*. 3 vols. New York: Springer-Verlag.

Nicholls, R.V. 1993. *Corpus Speculorum Etruscorum: Great Britain 2*. London: Cambridge University Press.

Nussbaum, M.C. 1978, rev. ed. 1985. *Aristotle's De Motu Animalium*. Princeton: Princeton University Press.

_____ 1987. “Saving Aristotle's Appearances.” In *Language and Logos: Studies in Ancient Greek Philosophy*, eds. M. Schofield and M. Nussbaum. New York: Cambridge University Press, pp. 267-293.

Nussbaum, M. and H. Putnam. 1992, repr. 1995. “Changing Aristotle's Mind.” In *Essays on Aristotle's* De Anima, eds. M.C. Nussbaum and A.O. Rorty. New York: Oxford University Press, pp. 27-56.

Nussbaum, M. and A.O. Rorty, eds. 1992. *Essays on Aristotle's* De Anima. New York: Oxford University Press.

Nutton, V. 2004. *Ancient Medicine.* New York: Routledge.

O'Brien, D. 1970. “The Effect of a Simile: Empedocles' Theories of Seeing and Breathing.” *Journal of Hellenic Studies* 90: 140-179.

Oleson, J.P. 1984. *Greek and Roman Mechanical Water-Lifting Devices: The History of a Technology*. Toronto: University of Toronto Press.

_____ ed. 2008. *The Oxford Handbook of Engineering and Technology in the Classical World*. New York.

Ortloff, C.R. 2009. *Water Engineering in the Ancient World: Archaeological and Climate Perspectives on Societies of Ancient South America, the Middle East, and South-East Asia*. New York: Oxford University Press.

Oppenheimer, J.R. 1956. “Analogy in science.” *American Psychologist* 11: 127-135.

Owen, G.E.L. 1986. “*Tithenai ta phainomena.*” In *Logic, Science and Dialectic: Collected papers in Greek philosophy*, ed. Martha Nussbaum. Duckworth.

Panofsky, E. 1991. *Perspective as Symbolic Form.* Cambridge, Mass.: MIT Press.

Panzerbieter, F. 1945. “Zu Empedokles.” *Zeitschrift für die Alterthumswissenschaft* 3: 883-893.

Park, D. 1997. *The Fire Within the Eye: A Historical Essay on the Nature and Meaning of Light*. Princeton University Press.

Pastoureau, M. 2001. *Blue: The History of a Color*, trans. M.I. Cruse. Princeton, New Jersey: Princeton University Press; orig. publ. as 2000. *Bleu, Histoire d’une couleur*. Paris: Éditions du Seuil.

Peck, A. 1942. “Appendix B: Σύμφυτον Πνεῦμα.” In *Aristotle: Generation of Animals,* Cambridge: Harvard University Press, Loeb Editions.

_____ 1953. “The Connate *Pneuma*: an Essential Factor in Aristotle’s Solutions to the Problems of Reproduction and Sensation.” In *Science, Medicine and History: Essays on the Evolution of Scientific Thought and Medical Practice Written in Honour of Charles Singer*, ed. E.A. Underwood. Oxford: Oxford University Press, pp. 111-121.

Pedersen, O. 1974, rev. ed. 1993. *Early Physics and Astronomy*. New York: Cambridge University Press.

Pender, E.E. 2003. “Plato on Metaphors and Models.” In *Metaphor, Allegory and the Classical Tradition*, ed. G.R. Boys-Stones. New York: Oxford University Press, pp. 55-82.

Pérez, J.A. 2011. “Location and Contexts of Toilets.” In *Roman Toilets: Their Archaeology and Cultural History*, eds. G.C.M. Jansen, A.O. Koloski-Ostrow and E. Moorman. Leuven: Peeters, pp.113-130.

Pigeaud, J. 1980. “La physiologie de Lucrèce.” *Revues des études latines* 58: 176-200.

Platt, A. 1921. “Aristotle on the heart.” In *Studies in the History and Method of Science*, vol. 2, ed. C. Singer, pp. 520-532.

Polito, R. 1999. “On the Life of Asclepiades of Bithynia.” *Journal of Hellenic Studies* 119: 48-66.

_____ 2006. “Matter, Medicine, and the Mind: Asclepiades vs. Epicurus.” *Oxford Studies in Ancient Philosophy* 30: 285-335.

_____ 2007. “Frail or Monolithic? A Note on Asclepiades’ Corpuscles.” *Classical Quarterly* 57: 314-17.

Prager, F.D. 1974. *Philo of Byzantium: Pneumatica*. Wiesbaden: Dr. Ludwig Reichert Verlag.

Prantl, C. 1849. *Aristoteles über die Farben*. München: Kessigner.

Price, D. de Solla. 1974. “Gears from the Greeks: The Antikythera Mechanism: A Calendar Computer from ca. 80 B.C.” *Transactions of the American Philological Association* 64, no. 7: 1-70.

Rawson, E. 1982. “On the life and death of Asclepiades of Bithynia.” *Classical Quarterly* 32: 358-70.

Ricoeur, P. 1978. *The Rule of Metaphor: Multi-disciplinary studies of the creation of meaning in language*. Toronto: University of Toronto Press.

Rihll, T.E. 2002. “Introduction: Greek Science in Context.” In *Science and Mathematics in Ancient Greek Culture*, eds. C.J. Tuplin and T.E. Rihll. Oxford: Oxford University Press, pp. 1-21.

Roby, C. 2010. *The encounter of knowledge: technical ekphrasis between Alexandria and Rome.* PhD diss., Stanford University.

Rocca, J. 2003. *Galen on the Brain: Anatomical Knowledge and Physiological Speculation in the Second Century AD*. Leiden: Brill.

Ross, G.R.T., trans. 1906. *Aristotle: De Sensu and De Memoria*. Cambridge: Cambridge University Press.

Ross, W. D., ed. 1949. *Aristotle's Prior and Posterior Analytics: A Revised Text with Introduction and Commentary*. Oxford: Clarendon Press.

Rudolph, K.C. 2011. “Democritus’ Perspectival Theory of Vision.” *Journal of Hellenic Studies* 131: 67-83.

Rüsche, F. 1930. *Blut, Leben Und Seele, Ihr Verhaeltnis Nach Auffassung Der Griechischen Und Hellenistischen Antike, Der Bibel Und Der Alten Alexandrinischen Theologen*. Paderborn.

Russo, L. 2004. *The Forgotten Revolution: How Science Was Born in 300BC and Why It Had to Be Reborn*, trans. S. Levy. Berlin: Springer.

Saito, K. 2006. "A Preliminary Study in the Critical Assessment of Diagrams in Greek Mathematical Works." *Sciamus* 7: 81-144.

Salem, J. 1996. *Démocrite: Grains de poussière dans un rayon de soleil.* Paris: Vrin, Bibliothèque d'histoire de la philosophie.

Sarton, G. 1959. *Hellenistic Science and Culture in the Last Three Centuries B.C.* New York: Dover.

Sassi, M.M. 1978. *Le teorie della percezione in Democrito*. Florence: La Nuova Italia.

Schatzberg, E. 2006. "Technik Comes to America: Changing Meanings of Technology before 1930." *Technology and Culture* 47: 486–512.

Schiefsky, M. 2007. "Art and Nature in Ancient Mechanics." In *The Artificial and the Natural: an Evolving Polarity*, eds. B. Bensaude-Vincent and W. Newman, pp. 67-108.

_____ 2008. "Theory and Practice in Heron's *Mechanics*." In *Mechanics and Natural Philosophy Before the Scientific Revolution*, eds. W.R. Laird and S. Roux. Dordrecht: Springer.

Schneider, G. 1818. *Theophrasti Eresii quae supersunt opera.* Leipzig: Teubner.

Schofield, M. 2011. "*Phantasia* in *De Motu Animalium*." In *Moral Psychology and Human Action in Aristotle*, eds. Michael Pakaluk and Giles Pearson. New York: Oxford University Press, pp. 119-134.

Schuhl, P.-M. 1947. *Machinisme et philosophe*, Paris: Félix Alcan.

Sedley, D. 1982. "On signs." In *Science and Speculation: Studies in Hellenistic Theory and Practice*, eds. J. Barnes et al. Cambridge: Cambridge University Press, pp. 239-72.

_____ 1992. "Empedocles' Theory of Vision and Theophrastus' *De sensibus*." *Theophrastus: His Psychological, Doxographical, and Scientific Writings*, eds. W.W. Fortenbaugh and D. Gutas. New Brunswick, New Jersey: Transaction Publishers, pp. 20-31.

_____ 2007. *Creationism and its Criticism.* Berkeley: University of California Press.

Shapin, S. 1989. "The Invisible Technician." *American Scientist* 77: 554-563; repr. 1994. *A Social History of Truth*. Chicago: University of Chicago Press, pp. 355-408.

Shapin, S. and S. Schaffer. 1985. *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life.* Princeton, N.J.: Princeton University Press.

Sheth, F.A. 2009. *Toward a Political Philosophy of Race*. Albany: State University of New York Press.

Seigel, R. 1959. "Theories of Vision and Color Perception of Empedocles and Democritus; Some Similarities to the Modern Approach." *Bulletin of the History of Medicine* 33, no. 2: 145-159.

_____ 1970a. *Galen on Sense Perception.* Basel: S. Karger.

_____ 1970b. "Principles and Contradictions of Galen's Doctrine of Vision." *Sudhoffs Archiv: Zeitschrift für Wissenschaftsgeschichte* 54: 261-76.

Simon, G. 1988. *Le Regard, L'Être et L'Apparence dans L'Optique de L'Antiquité*. Paris: Éditions du Seuil.

Simon, H.A. 1956. "Reply: Surrogates for Uncertain Decision Problems." *Office of Naval Research*, January; repr. 1982. *Models of Bounded Rationality, Volume 1, Economic Analysis and Public Policy*. Cambridge, Mass.: MIT Press, pp. 235–44.

Sinisgalli, R. 2012. *Perspective in the Visual Culture of Classical Antiquity*. New York: Cambridge University Press.

Slakey, T. 1961. "Aristotle on Sense Perception." *The Philosophical Review* 70, no. 4: 470-484.

Smith, M. A. 1988. "The Psychology of Visual Perception in Ptolemy's *Optics*." *Isis* 79: 189-206.

_____ 1996. *Ptolemy's Theory of Visual Perception: An English Translation of the* Optics *With Introduction and Commentary*. Philadelphia: Transactions of the American Philosophical Association.

_____ 1999. *Ptolemy and the Foundations of Ancient Mathematical Optics: A Source Based Guided Study*. Philadelphia: Transactions of the American Philosophical Society.

Smith, P. 2004. *The Body of the Artisan: Art and Experience in the Scientific Revolution*. Chicago: University of Chicago Press.

Smith, R. 1995. "Logic." In *The Cambridge Companion to Aristotle*, ed. J. Barnes. New York: Cambridge University Press, pp. 27-65.

Solmsen, F. 1961. "Greek philosophy and the discovery of the nerves," *Museum Helveticum* 18: 150-197; repr. as 1968c. *Kleine Schriften*, 3 vols. Hildesheim: Georg Olms, vol. 1, pp. 536-82.

_____ 1968a. "Nature as Craftman in Greek Thought." in *Kleine Schriften*, 3 vols. Hildesheim: Georg Olms, vol. 1, pp. 332-355; orig. publ. in 1963. *Journal of the History of Ideas* 24: 473-496.

_____ 1968b. "On Plato's Account of Respiration." In *Kleine Schriften*, 3 vols. Hildesheim: Georg Olms, vol. 1, pp. 583-587; orig. publ. in 1956. *Studi italiani di filologia classica* 27-28: 544-548.

Sorabji, R. 1972a, repr. 2004. *Aristotle on Memory*. London: Duckworth.

_____ 1972b. "Aristotle, Mathematics, and Colour." *Classical Quarterly* 22, no. 2: 293-308.

_____ 1974. "Body and soul in Aristotle." *Philosophy* 49: 63-89; repr. in 1979. *Articles on Aristotle*, ed. J. Barnes, M. Schofield and R. Sorabji, London: Duckworth, pp. 42-64.

_____ 1992. "Intentionality and physiological processes: Aristotle's theory of sense-perception." In *Essays on Aristotle's* De Anima, eds. Nussbaum, M. and A.O. Rorty. New York: Oxford University Press, pp. 195-225.

Stein, R. 2004. "Roman wooden force pumps: A case study in innovation." *Journal of Roman Archaeology* 17: 221-250.

Stothers, R. 2009. "Ancient Meteorological Optics." *Classical Journal* 105, no. 1: 27-42.

Stratton, G.M. 1917. *Theophrastus and the Greek Physiological Psychology Before Aristotle*. New York: MacMillan Company.

Swaddling, J. 2001. *Corpus Speculorum Etruscorum: Great Britain 1.* London: The British Museum Press.

Switalski, B. W. 1902. *Des Chalcidius kommentar zu Plato's Timaeus: eine historisch-kritische Untersuchung*. Münster.

Tarán, L. 1975. *Academica: Plato, Philip of Opus, and the Pseudo-Platonic* Epinomis. Philadelphia: American Philosophical Society.

Taub, L. 1993. *Ptolemy's Universe: The Natural Philosophical and Ethical Foundations of Ptolemy's Astronomy.* Chicago: Open Court.

_____ 2003. *Ancient Meteorology*. New York: Routledge.

Taylor, A.E. 1928. *A Commentary on Plato's Timaeus*. Oxford: Clarendon Press.

Taylor, C.C.W. 1999. *The Atomists: Leucippus and Democritus*. Toronto.

Temkin, O. 1951-53. "On Galen's Pneumatology." *Gesnerus* 8: 180-89; repr. in 1977 *The Double Face of Janus and Others Essays in the History of Medicine*. Baltimore: Johns Hopkins University Press, pp. 154-161.

Thomson, H.A. and R.E. Wycherley. 1972. *The Agora of Athens: the history, shape and uses of an ancient city center*. Princeton, New Jersey: The American School of Classical Studies at Athens.

Tieleman, T. 2003. *Chrysippus'* On Affections: *Reconstruction and Interpretation*. Leiden: Brill.

Tobin, R. 1990. "Ancient Perspective and Euclid's Optics." *Journal of the Warburg and Courtauld Institutes* 53: 14-41.

Tölle-Kanstenbein, R. 1991. "Entlüftung antiker Wasserleitungsrohre." *Archäologischer Anzeiger*: 25-30.

_____ 1994. *Das archaische Wassleitungensnetz für Athen und seine späteteren Bauphasen*. Mainz.

_____ 1996. "Das archaische Wasserleitungsnetz für Athen." In *Cura Aquarum in Campania*, suppl. 4., eds. N. de Haan and G.C.M. Jansen. Leiden: BABESCH, pp. 129-136.

Toomer, G.J. 1976. "Ptolemy." In *Dictionary of Scientific Biography*, vol. 11, ed. C.C. Gillispie. New York: Scribner.

_____ trans. 1984. *Ptolemy's Almagest*. London: Duckworth.

Vallance, J.T. 1990. *The Lost Theory of Asclepiades of Bithynia*. Oxford: Clarendon Press.

van Leeuwen, J. 2012. *The Traditions of the Aristotelian* Mechanics: *Texts and Diagrams*. PhD diss., Humboldt-Universität, Berlin.

van der Waerden, B.L. 1959. "Klaudios Ptolemaios." In *Paulys Realencyclopädie der classischen Altertumswissenschaft*, vol. 23.2, Munich, pp. 1788-1859.

Vegetti, M. 1995. "L'épistémologie d'Érasistrate et la technologie hellénistique." In *Ancient Medicine in its Socio-Cultural Context*, 2 vol., ed. Ph.J. van der Eijk, et al. Amsterdam: Brill, pp. 461-471.

Verdenius, W.J. 1948. "Empedocles' Doctrine of Sight." *Studia Varia Carolo Guilielmo Volgraff*. Amsterdam: North-Holland Publishing Company.

Volk, K. 2010. "Literary Theft and Roman Water Rights in Manilius' Second Proem." *Materiali e discussioni per l'analisi dei testi classici* 65: 187-197.

von Fritz, K. 1953. "Democritus' theory of vision." In *Science, Medicine and History: Essays on the Evolution of Scientific Thought and Medical Practice Written in Honour of Charles Singer*, ed. E.A. Underwood. Oxford: Oxford University Press, pp. 83-99.

_____ 1971. *Grundeprobleme der Geschichte der antiken Wissenschaft*. Berlin: Walter de Gruyter.

von Staden, H. 1989. *Herophilus: the Art of Medicine in Early Alexandria*. Cambridge: Cambridge University Press.

_____ 1992. "Discovery of the Body." *Yale Journal of Biology and Medicine* 65: 223-41.

_____ 1996. "Body and Machine: Interactions between Medicine, Mechanics, and Philosophy in Early Alexandria." In *Alexandria and Alexandrianism*, ed. K. Hamma. Malibu, Califor.: The J. Paul Getty Museum, pp. 85-106.

_____ 1997. "Teleology and Mechanism: Aristotelian Biology and Early Hellenistic Medicine." In *Aristotelische Biologie: Intentionen, Methoden, Ergebnisse*, W. Kullmann and S. Follinger. Stuttgart: Franz Steiner Verglag, pp. 183-208.

_____ 1998. 'Andréas de Caryste et Philon de Byzance: médecine et méchanique à Alexandrie." In *Sciences exactes et sciences appliqués à Alexandrie*, eds. G. Argoud and J.-Y. Guillaumin. St. Étienne: Université de Saint-Etienne, pp. 147-172.

_____ 2007. "*Physis* and *Technê in Greek Medicine*." In *The Artificial and the Natural: an Evolving Polarity*, eds. B. Bensaude-Vincent and W. Newman. Cambridge, Mass.: MIT Press, pp. 21-49.

Wachtler, J. 1896. *De Alcmaeone Crotoniata*. Leipzig: Teubner.

Wade, N. 1998. *A Natural History of Vision*. Cambridge, Mass.: MIT Press.

Webster, C. 2014, forthcoming. "Euclid's *Optics* and Geometrical Astronomy." *Apeiron* 47.4.

Wedin, M.W. 1988. *Aristotle on Mind and the Imagination*. New Haven: Yale University Press.

Wehrli, F. 1850. *Die Schule des Aristoteles*, vol. 5. Basel.

Weitzmann, K. 1970, 2nd ed. *Illustrations in Roll and Codex: a study of the origin and method of text illustration*. Princeton: Princeton University Press.

_____ 1971. "The Greek Sources of Islamic Scientific Illustrations." *Studies in Classical and Byzantine Manuscript Illumination*, ed. Herbert L. Kessler. Chicago: University of Chicago Press.

_____ 1977. *Late Antique and Early Christian Book Illumination*. New York: George Braziller.

Wellmann, M. 1895. *Die Pneumatische Schule.* Berlin: Weidmannsche Buchhandlung.

_____ 1901. *Die Fragmente der sikelischen Ärtze Akron, Philistion und des Diokles von Karystos*. Berlin: Weidmannsche Buchhandlung.

_____ 1908. "Asklepiades aus Bithynien von einem herrschenden Vorurteil befreit." *Neue Jahrbücher* 21: 684-703.

White, J. 1956. *Perspective in Ancient Drawing and Painting*. London: Society for the Promotion of Hellenic Studies.

Wikander, O., ed. 2000. *Handbook of Ancient Water Technology*. Leiden: Brill.

Williams, G. 2013. *The Cosmic Viewpoint: A Study of Seneca's 'Natural Questions*.' New York: Oxford University Press.

Wilson, I.A. 2000. "Drainage and Sanitation." In *Handbook of Ancient Water Technology*, ed. O. Wikander. Leiden: Brill, pp. 151-179.

_____ 2002. "Machines, power and the ancient economy." *Journal of Roman Studies* 92: 1-32.

_____ 2008. "Hydraulic Engineering and Water Supply." In *The Oxford Handbook of Engineering and Technology in the Classical World*, ed. J.P. Oleson. New York: Oxford University Press, pp. 285-318.

Wilson, W. 2013. *Structure and Method in Aristotle's* Meteorologica*: A More Disorderly Nature*. New York: Cambridge University Press.

Woodcroft, B. 1851. *Heron, Pneumatica*. London: Charles Whittingham.

Woollam, D.H.M. 1958. "Concepts of the brain and its functions in classical antiquity." In *The History and Philosophy of Knowledge of the Brain and its Functions*, ed. F.L.N. Poynter. Springfield, Ill: Charles C. Thomas, pp. 5-18.

Worthen, T. 1970. "Pneumatic Action in the Klepsydra and Empedocles' Account." *Isis* 61: 520–530.

Wright, M.T. 2000. "Greek and Roman Portable Sundials An Ancient Essay in Approximation." *Arch. Hist. Exact Sci.* 55: 177-187.

Wright, M.R. 1981. *Empedocles: The Extant Fragments*. New Haven: Yale University Press.

Zeller, E. 1920-1923. *Der Philosophie der Griechen*, 3 vols. Leipzig: O.R. Reisland.