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CHAPTER 1

Introduction: centers and orientations

The historiographical problem

It is something of a commonplace to say that the seventeenth century witnessed a shift from viewing the natural world as fundamentally spherical to viewing the universe as fundamentally rectilinear. This move toward rectilinearity is evident in the emergence of all the hallmarks of "classical" science. The dissolution of the heavenly spheres, the replacement of equilibrium by collision as the model of mechanical interaction, the abandonment of Aristotelian natural place, and the all-important development of rectilinear inertia to supplant natural motion and impetus all display the general trend. Nevertheless, while these developments have been extensively studied individually, the conceptual shift common to all has not been satisfactorily addressed. Though most scholars would immediately recognize and acknowledge the existence and importance of the adoption of a rectilinear framework in the early modern physical sciences, none has satisfactorily detailed how this came to pass.

Many scholarly studies have sought answers to this question in the metaphysical understanding of space during the period.[1] According to these accounts, a rectilinear framework was somehow adopted alongside a shift in the understanding of space considered as a substantial thing. Their focus, therefore, is on the history of debates about space's ontological properties – its infinitude, eternality, vacuity, absoluteness, and so on. However, as I argue more extensively below, this emphasis is misplaced. Abstract speculation about the nature of space was too divorced from the changing explanations of the behavior of bodies that formed the physical core of the Scientific Revolution. The move toward rectilinearity was a change in the understanding

[1] Classic treatments include Jammer (1954), Koyré (1957), Grant (1981). See also Burtt (1954), Butterfield (1957), Dijksterhuis (1961),Toulmin and Goodfield (1961), Koestler (1968), Huggett (1999), Barbour (2001). To be fair, Jammer's treatment of the ancient and medieval periods focuses on the epistemic import of space. In fact, Jammer's work constitutes an appropriate prelude to my own. Nevertheless, his treatment of the early modern period veers toward the metaphysical.

of phenomena *in* space, not the nature of space itself. For example, sometime in the early modern period, authors decided that rectilinear translations were instances of uniform change. This decision was not determined by their views about the plenitude or immobility of space. Rather, it came about in their construction of theoretical knowledge about the behavior of physical objects. What is needed, then, is not another history of spatial ontology, but a history of spatial *epistemology*. This is what I attempt in the following.

In particular, this book will argue that *representation of space* is the appropriate unit by which to analyze the development of rectilinearity in classical science. As will be expressed more precisely below, a representation of space is part of a descriptive framework by which spatial properties and relations are described and explained. Thus, the "something" that changed during the seventeenth century was the prevailing representation of space. The shift that accompanied the emergence of modern science can be described as a move from a centered representation of space to an oriented representation of space. Authors described and explained spatial properties spherically, in relation to centers, at the beginning of the period and rectilinearly, in relation to orientations, at its end.

So baldly stated, this thesis seems blatantly and perniciously anachronistic. It imputes a contemporary notion of my own devising into the work of historical authors, and thus threatens to distort the resulting historical account. I am compelled, therefore, to offer a preliminary defense of the analytical frame I use to approach the history of the Scientific Revolution. The thoroughgoing argument in favor of my approach will be the analysis itself. The coherence and accuracy of the account presented in the rest of this volume will be the justification of my claims and the measure of their success. In the meantime, however, I must show that the authors here examined made use of what I am calling representations of space, such that they are appropriate objects to seek and characterize in historical work, and not mere anachronistic figments. There are two ways I might accomplish this task. The first is to identify pieces of text in which authors explicitly state their representations of space. This path is not available, since explicit expressions of a representation of space are very rare, though not entirely absent, in the work of early modern natural philosophers. This is not surprising. Indeed, it will be argued below that explicit statements regarding representations of space should not be expected of *any* author, since a representation of space comprises commonly held, "ordinary" concepts that seem obvious in most contexts. Hence, authors usually do not need to elaborate a representation of space in order to effect meaningful communication.

The second path, which I will follow, is to argue that a representation of space is a necessary part of any physical understanding of the natural world, and thus an essential part of the work of any natural philosopher. If I can establish the *a priori* expectation of finding a representation of space implicit or explicit in any attempt to provide physical understanding, I can then reasonably seek the representation of space contained in the work of early modern authors, or any other for that matter. One need not fear pernicious anachronism due to the illicit distortion of historical texts. Notice, however, that establishing the necessity of a representation of space makes a claim about physical understanding in general that transcends temporal period. It entails a *philosophical* argument proceeding from basic intuitions about the nature of scientific understanding. The remainder of this introduction sketches just such a philosophical argument.

The philosophical argument for the necessity of representations of space does not complete the historiographical project, however. One must also show how the proposed unit of analysis is to be identified in historical texts, especially since it is usually implicit. This introduction proposes a method for identifying representations of space by textual interrogation. Finally, it must be demonstrated that representations of space are actual. That is, it needs to be shown that representations of space in fact describe the historical phenomenon in question: the shift from a spherical to a rectilinear worldview. The latter demonstration proceeds in the course of the following narrative.

It follows that this will be a work of integrated history and philosophy of science. On the one hand, the subject is philosophical. I will examine the spatial epistemology of early modern natural philosophy. In particular, I will suggest that physical theories necessarily contain descriptive frameworks that coordinate their explanatory principles with phenomena, and that representations of space are part of these descriptive frameworks. On the other hand, the argument itself will be historical. I will detail how a shift in descriptive frameworks occurred in the work of several seventeenth-century authors by offering a chronological reconstruction based on the examination of representations of space. These aims are meant to be mutually reinforcing. Representations of space form the analytic framework for the historical account, and the historical account establishes the constitutive and causal role of representations of space in physical thought. The coherence and likelihood of the historical narrative will support the plausibility of the philosophical analysis by which it is constructed, and *vice versa*. The aim is to make the philosophical and historical case *at the same time*.

Explanations, descriptions, frameworks, and theories

This is not the place for an extended philosophical disquisition. The bulk of my argument for the epistemology of science I am here proposing will reveal itself in the course of the narrative to follow. However, in order to identify the analytical tools with which I am working, I must first offer a sketch of my view of the structure of scientific theories. At this level of generality, I take my account to be non-controversial (if there is such a thing) and in keeping with current trends in philosophy of science.[2] The details are more contentious, naturally; I hope eventually to offer an expanded exposition of my position, using the present work as evidence, but I leave that for another venue.

Science offers explanations of the natural world. Any scientific theory, that is, purports to explain the phenomena within its domain. However, explanations necessarily rely on descriptions. In order to construct an explanation, one must first specify the phenomena to be explained with a definite description. Moreover, explanations themselves must involve at least some descriptions of phenomena. If an explanation is meant to show how the properties and relations of objects account for the feature of the world to be explained, then those properties and relations must be described in the course of the explanation. For example, an explanation might include descriptions of the initial conditions that occasion the target phenomenon; or it might include a description of the physical context in which the phenomenon took place (the forces acting and so on).[3] The ability to explain depends on the ability to describe.

The latter ability, in turn, is provided by a descriptive framework that coordinates descriptions with the features of the phenomena they represent. This framework consists of the criteria by which the propriety of the application of a description is judged – i.e., the verification conditions of the description. It specifies which phenomena count as instances of a description. To illustrate, consider the description ‘the apple falls down’. This statement describes the behavior of a physical object. It specifies an

[2] The layered epistemology outlined here has its roots in the Fregean distinction between sense and reference. On my account, a description gets part of its meaning from its sense relative to the explanations provided by the theory and part from its reference in the phenomena as determined by the coordinative framework. Versions of this layered view, based on a similar semantic distinction, are widespread. I take my coordinative framework, at least in general terms, to be a reflection of Poincaré’s (1905) conventional definitions, Reichenbach’s (1920, 1958) relativized *a priori* and coordinative definitions, Carnap’s (1950) linguistic frameworks, Putnam’s (1962) framework principles, Kitcher’s (1978) reference potentials, van Fraassen’s (2008) representing-*as* (opposed to a theory’s representing-*that*), and Friedman’s (1999, 2001) constitutive *a priori*.

[3] For classic perspectives on descriptions in explanations, see Davidson (1967), Levin (1976),Woodward (1993).

object – the apple – as well as its behavior – a particular form of motion, falling. The statement also specifies the direction of the motion – down. Altogether, then, 'the apple falls down' can be comprehended as a meaningful description of a phenomenon. It specifies a certain phenomenon or fact about the world: the behavior of the apple – i.e., its motion in a particular manner in a particular direction. The meanings of 'apple', 'falls', and 'down' in this description, however, are not transparently intelligible. These terms must be coordinated with features of the phenomena in order for the meaning of the description to be made patent. 'Apple' must be coordinated with a particular object or set of objects. The term 'falls' must be coordinated with a particular kind of accelerated motion. 'Down' must be coordinated with a specific direction or trajectory. Such coordinations, taken together, constitute a descriptive framework. Thus, the descriptive framework enables an interpreter of the description 'the apple falls down' to identify the phenomenal objects described. For instance, the coordination of 'falls' allows the interpreter to understand that the apple undergoes an accelerated motion, while the coordination of 'down' picks out which direction is meant by the term. Similarly, an observer of a falling apple would employ his or her own coordinations of 'apple', 'falls', and 'down' in order to generate the description 'the apple falls down'.

Interpreters and generators of descriptions can only operate within the context of a descriptive framework that includes the coordinations of the elements of their descriptions. Put simply, the very possibility of description relies on the coordinative framework that links descriptive representations to the phenomena described. Only by using a descriptive framework can a generator of a description decide which terms adequately describe the phenomenon, or can an interpreter decode the resulting description. By the same token, users of a language hoping to communicate must share roughly similar descriptive frameworks. The possibility of communication breaks down when interlocutors possess different or radically divergent frameworks. Thus, if one were to say, on observing the falling apple, that "The apple falls umpwise," an interpreter of that description lacking the coordination criteria of 'umpwise' would be unable to understand the utterance. Likewise, if an interpreter's notion of "down" coordinated it with the direction toward the center of the sun, he or she would deny that 'the apple falls down' is an acceptable description of the phenomenon.

Theories offer explanations of phenomena, but, as we have seen, explanations include descriptions. It follows, therefore, that explanations can only be carried out in association with a descriptive framework. Since explanations require descriptions, and any description requires a framework by which the description is interpreted, explanations require coordinations. The coordinations contribute meaning to the descriptions that constitute the explanation. They establish the referential links between the explanation and the phenomena it purports to explain. Descriptive frameworks are necessary to bring phenomena under explanations, and thus necessary to make them intelligible.

Scientific theories must therefore contain two distinct epistemic levels. On the one hand, a theory provides explanatory resources that can account for the phenomena in its domain. On the other hand, a theory contains a descriptive framework that coordinates its explanations with those phenomena. Theories explain nothing without a descriptive framework in the context of which they are interpreted. Explanatory principles have no explanatory force – they are not explanations of anything – unless they are coordinated to some feature of the world by a description. Water, chemistry explains, is a certain combination of oxygen and hydrogen, but chemistry says nothing at all if does not also specify that 'water' signifies the stuff here in my glass or there in the river. Physics tells us that gravity causes an object to fall, but it also must tell us which motions count as 'falling'.

Representations of space

It remains to show that a *representation of space* is a necessary part of any *physical* theory. This is accomplished simply by definition: a representation of space is the subset of coordinations in a descriptive framework that concern spatial properties and relations. It includes, among many others, the coordinations of 'up', 'down', 'above', 'below', 'far', 'near', 'straight', 'curved', and so on. A representation of space is therefore the set of coordinations that underwrites descriptions of directions, locations, sizes, shapes, distances, and any other spatial property or relation. Hence, a representation of space is an essential element of the explanation of physical phenomena, insofar as such phenomena occur in physical space and physical explanations concern their behavior in that space. If an explanation refers to spatial properties and relations (and all the physical explanations I am interested in do), it calls upon a representation of space.[4]

[4] Kant used the term 'representation of space' to refer to the "form of outer intuition." In the Transcendental Aesthetic, he argued that a representation of space is the means by which sensory experience is ordered and thereby rendered intelligible (1998, 175). Though I do not agree with Kant that a Euclidean, oriented representation of space is a *necessary* feature of human cognition, I do think some representation of space is a necessary, *a priori* element of theoretical understanding. Hence, I conscientiously adopt Kant's term in order to refer to something very similar to what he seems to have had in mind.

A representation of space, however, can be characterized as more than just a bare set of coordinations. The coordinations in a representation of space are not held *in vacuo*, one by one. Various coordinations relate to the same objects, forming coordinative complexes and structures. For example, "up" is (usually) the opposite of "down." If 'down' is coordinated with the direction toward a stipulated location, 'up' is directly away from the same location. Also, the coordinations of 'above' and 'below', 'top' and 'bottom', etc., will refer to the same location, such that if "above" is further from the location, "below" is nearer, "top" is furthest, and "bottom" is nearest. The interrelations between the coordinations included in this representation of space form a coherent structure, built around a single presupposed location in relation to which each coordination is established.

These structured interrelations among coordinations make it possible to characterize the "shape" of a representation of space. If the coordinations in a representation of space all relate to a presupposed, privileged location, then directions, such as "up" and "down" will converge or diverge toward or away from the presupposed location. That is, the directions an observer employing this representation of space will describe as "down" will converge toward the central point his or her coordination criterion for 'down' relates to. Each region of space may also be conceived with a determinate privileged orientation – e.g., the direction toward or away from the privileged location. The observer will be able to say without any ambiguity which way is "up" or "down." And different regions of space will be distinguishable from one another by their distance from the privileged location. The observer, therefore, will be able to describe regions of space as "higher" or "lower." Put another way, a representation of space that presupposes a single privileged location is convergent, anisotropic, and heterogeneous. This is a *centered* representation of space.

Consider, by contrast, a representation of space in which terms are coordinated by relation to an arbitrary line or axis, rather than a privileged location. In this case, to describe spatial properties and relations, one must first specify the orientation to which descriptions are referred. 'Down' might then be coordinated with the direction parallel to the orientation in one sense, 'up' with the direction parallel to the orientation in the other. Similarly, 'above' would be further along the orientation in the "up" direction, 'below' would be further along the "down" direction. Here, directions described similarly will be parallel to each other. The direction described as "up" or "down" in one part of space is parallel to the direction described as "up" or "down" in another.

Moreover, without a presupposed privileged location by which locations could be uniquely specified, there would be no way to determinately distinguish different parts of space. There is nothing inherently distinguishing about the way any location is described. No feature of the descriptive framework allows a unique specification of place. One region of space might be correctly described as "higher" than another, but it could also be described as "lower" than a third. An observer can describe locations only relative to other locations. Consequently, descriptions of locations require the prior arbitrary stipulation of a reference point whose location is not itself specified. In sum, an *oriented* representation of space is isotropic, self-parallel, and homogeneous.[5]

This discussion is not meant to suggest that representations of space fall neatly into two categories: centered and oriented. There could be many other varieties of representation of space, as well as countless variations within each kind of spatial framework. Each author one encounters might employ a slightly different descriptive scheme. The point here is simply that it is possible to characterize the general shape of a representation of space. It makes sense to talk about a "centered" or "oriented" representation of space. In particular, one can meaningfully assert that the development of classical science included a shift from a prevailing centered representation of space to a prevailing oriented representation of space. This is a claim open to historical investigation.

A representation of space has special significance for the theoretical treatment of motion. Representations of space determine the phenomenal import of descriptions of directions and distances. In particular, they determine what counts as the same direction and the same distance in different locations and times. Consequently, a representation of space picks out what can be described as "the same motion" from place to place and moment to moment. As will be seen in relation to the historical examples discussed later in this chapter, this function of a representation of space is essential to any physical theory, since it identifies which features of the phenomena stand in need of explanation by a theory. Newtonian physics, for instance, says that motion is conserved. Yet the theory also coordinates 'conserved motion' with bodies moving uniformly along straight lines. The representation of space associated with the theory picks out the phenomena described as conserved motions and explicable as such.

Along these lines, it helps to point out the contemporary correlate of this historical discussion. What I am after is the *affine structure* of pre-modern and

[5] This kind of spatial framework is commonly called *Euclidean*, since its structure is similar to that of "Euclidean" geometry. The label, however, is misleading, since Euclid himself was ecumenical in his approach to geometry. His methods presupposed, on an equal footing, both lines, in the form of the straight edge, and central points, in the form of the compass point. Someone trying to describe phenomena could appeal to Euclid's proofs, whether his own representation of space was centered, "Euclidean," or otherwise.

classical physics. In relativistic physics, an affine structure determines what counts as the "same" direction through space, and it fixes, in turn, the inertial trajectories of bodies. Thus, the affine structure specifies what phenomena are described as "simple motions" – motions that are unchanging and need no explanation other than the conservation of prior motion. Calculation of the affine structure is part of the solution to the Einstein field equations determined by the distribution of mass and energy. The affine structure is therefore *a posteriori* in the sense that it depends on the actual distribution of matter and energy in a spacetime manifold. By the same token, determination of the simple motions is an explicit part of the physical theory, and the representation of space implied by the theory can be discovered by a straightforward inspection of its mathematical expression. The coordination of explanations with phenomena is a part of the theory itself. A physicist must state from the outset what his or her descriptions of motions *mean*.[6]

Of course, before the advent of relativity, representations of space were *a priori* in that space was presumed to have a certain structure within which bodies moved. Einstein's essential realization, which was partly the result of influence by Poincaré and Mach, was that the structure of space (and time) is not fixed, but affected by the bodies in it. In other words, he realized that the representation of space was part of physics, not a background assumption. Einstein did not create the notion of affine structure or the question of representation of space out of whole cloth. He simply made it a subject of empirical investigation. By the same token, though, the representation of space was an essential part of pre-relativistic physics. There is a pre-history of affine structures – a history of representations of space.

Representations of space are not anachronistic figments. They are a necessary part of any physical understanding, since they enable the phenomena to be described and explained *in space*. Though representations of space can be constrained by the context of a phenomenon, they are not trivial. Therefore, the historian of scientific understanding can and should seek the representations of space associated with physical explanations of phenomena. That is what I attempt to do in this book.

Interrogating texts

At this point, however, one encounters a difficulty. One should not expect to find explicit statements of an author's representation of space in his or her texts. More often than not, the representation of space goes without stating.

6 See, e.g., Sklar (1974), Friedman (1983).

On the one hand, descriptive frameworks can be very complicated, and, since they are prior to the use of a description, they are not themselves expressible. One might talk *about* the coordinations, and thus one might attempt to describe a descriptive framework, but the framework itself is beyond expression. Furthermore, some descriptive coordinations may refer to exemplars – particular objects – that cannot appear in sentential rules. One might have in mind one's own dog when judging whether another object can be described as "a dog."[7] Other criteria might be simply heuristic and subject to inexpressible exceptions. It can be difficult even to *try* to express the conditions that constitute a description's coordination and thus hard to identify precisely the phenomenal extension of that description.

On the other hand, and equally problematic, is the fact that failures of communication caused by divergent descriptive frameworks are rare and limited to extreme cases. In the case of neologisms and obscure terms, an author is expected to provide explicit definitions – one should state clearly the meaning of 'umpwise' before expecting an audience to agree that an apple falls umpwise. However, the vast majority of coordinations are anything but novel or obscure. In normal communication, one can assume that competent users of a language have learned, through the process of language acquisition, a coordinative framework similar to one's own. Thus, explicit definitions are seldom called for, and authors, even in science, can typically describe phenomena without explicating the frameworks they employ.

This is especially true in the case of representations of space. A representation of space is necessary for and prior to the description and explanation of physical phenomena, but it is, on the one hand, itself difficult to express (as are all descriptive frameworks), and, on the other, often obvious or simply conventional. We all have "ordinary" notions of "up," "down," and so on, even if these are not the precise notions used in physical explanations. Thus, readers already have some sense of an author's meaning when it comes to descriptions of spatial properties and relations. Explicit definitions of such terms would seem redundant. Moreover, particular physical situations usually present obviously privileged objects and a convenient geometric structure. These tend to constrain our "ordinary" spatial frameworks to a limited set that are similar enough to allow meaningful communication. We tend, for example, to employ a centered representation of space when observing the

[7] This is a particularly simple example. In fact, exemplars may be quite technical and complicated. Galileo's appeal to the behavior of bitumen on a hot iron pan, for example, helped make his description of sunspots intelligible. Similarly, he often used the lever to generate descriptions of phenomena, as in the cases of floating bodies and inclined planes. Machamer (1995) calls these exemplars "models of intelligibility." See also Feldhay (1995).