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Tian Yu Cao
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Introduction

The treatment of the subject in this monograph is selective and interpretive, motivated and guided by some philosophical and methodological considerations, such as those centered around the notions of metaphysics, causality, and ontology, as well as those of progress and research programme. In the literature, however, these notions are often expressed in a vague and ambiguous way, and this has resulted in misconceptions and disputes. The debates over these notions (and related motivations) concerning their implications for realism, relativism, rationality, and reductionism have become ever more vehement in recent years, because of a radical reorientation in theoretical discourses. Thus, it is obligatory to elaborate as clearly as I can these components of the framework within which I have selected and interpreted the relevant material. I shall begin this endeavor by recounting in Section 1.1 my general view on science. After expounding topics concerning the conceptual foundations of physics in Sections 1.2–1.4, I shall turn to my understanding of history and the history of science in Section 1.5. The introduction ends with an outline of the main story in Section 1.6.

1.1 Science

Modern science as a social institution emerged in the 16th and 17th centuries as a cluster of human practices by which natural phenomena could be systematically comprehended, described, explained, and manipulated. Among important factors that contributed to its genesis, we find crafts (instruments, skills, and guilds or professional societies), social needs (technological innovations demanded by emerging capitalism), magic, and religion. As an extension of everyday activities, science on the practical level aims at solving puzzles, predicting phenomena, and controlling the environment. In this regard, the relevance of crafts and social needs to science is beyond dispute.[1]

Yet, as a way of meeting human beings' curiosity about the nature of the cosmos in which they live, of satisfying their desire to have a coherent conception of the physical world (an understanding of the construction, structures, laws, and workings of the world, not in terms of its appearances but in terms of its reality, that is, in terms of its true picture, its ultimate cause, and its unification), more pertinent to the genesis of modern science, however, were certain traditions in magic and religion, namely the Renaissance Hermetism

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and the Protestant Reformation, as pointed out by Frances Yates (1964) and Robert Merton (1938), respectively. In these traditions, the possibility and ways of understanding, manipulating, and transforming the physical world were rationally argued and justified by appealing to certain preconceptions of the physical world, which were deeply rooted in the human mind but became dominant in modern thoughts only through the religious Reformation and the rise of modern science.

The most important among these preconceptions presumes that the physical world has a transcendental character. In Hermetic tradition, a pagan cosmology of universal harmony was assumed, in which idols possessed occult power, yet humans shared with these transcendental entities similar properties and capacities, and could have exchange and reciprocity with them. In religious traditions, the transcendence of the world lay in God’s consciousness, because the very existence of the world was a result of God’s will, and the working of nature was designed by him. This transcendence assumption has underlain the basic ambiguity of modern science, which is both mystical and rational at the same time. It is mystical because it aims at revealing the secrets of nature, which are related either to the mysteriously preestablished universal harmony or to divine Providence. It is rational because it assumes that the secrets of nature are approachable by reason and accessible to human beings. The rationalist implication of the transcendence assumption was deliberately elaborated by Protestant theologians in their formulation of cosmology. Not only was the formulation, in addition to other factors, crucial to the genesis of modern science but it has also bequeathed some essential features to modern science.

According to Protestant cosmology, God works through nature and acts according to regular laws of nature, which are consciously designed by him and thus are certain, immutable, inevitable, and in harmony with each other. Since God’s sovereignty was thought to be executed through regular channels and reflected in the daily happenings of the world, the orderly world was believed to be fully susceptible to study by scientists who tried to find out causes and regularities of natural phenomena with the help of their empirical experience. The cosmological principles of Protestant theology (which related God with natural phenomena and their laws) provided religious motivations and justifications for the study of nature. For the followers of Calvinism, the systematic, rational, and empirical investigations of nature were vehicles to God or even the most effective means of begetting in man a veneration of God. The reason for this was that the incessant investigations of, and operations upon, nature would gradually unfold reason, increasingly approximate perfection, and finally discover the true nature of the works of God and glorify God. This transcendental motivation has guided modern theoretical sciences ever since their emergence. And a secularized version of it is still prevalent in contemporary scientific literature.[2]

Although its ethical and emotional motivations for rationally and systematically understanding and transforming the world originated from Puritan values, which were in concordance with the ethics of capitalism (systematically calculated conduct in the domains of economy, administration, and politics), modern science as an intellectual pursuit was mainly shaped by the revived ancient Greek atomism and rediscovered

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Archimedes and particularly by the Renaissance Neoplatonism. The latter was tied to Platonic metaphysics or to a mystical cosmology of universal harmony and system of correspondence, yet aimed at a rational synthesis of human experience of natural phenomena with the help of mathematical mysticism and mathematical symbolism, and thus attracted the curiosity and fired the imagination of Copernicus and Kepler, as well as Einstein, Dirac, Penrose, Hawking, and many contemporary superstring theorists.

Another preconception prevalent in the Renaissance magic was about the “uniformity of nature.” Its magicians believed that same causes always led to same effects, and as long as they performed the ritual acts in accordance with the rules laid down, the desired results would inevitably follow. Although the belief in associative relations between natural events had only an analogical basis, it was surely the precursor of the mechanical idea that the succession of natural events is regular and certain and is determined by immutable laws; that the operation of laws can be foreseen and calculated precisely; and that the element of chance and accident is thus banished from the course of nature.

The carving out of a domain of nature with its regular laws helped to move God further and further away from the ideas of causality in empirical science, to demarcate nature as separated from the domain of supernatural phenomena, and to take naturalistic causes as a ground for the explanation of natural phenomena. Related with this was the belief that natural forces were manipulatable and controllable. Without this belief, there would be no practice in astrology, alchemy, and magic operated in symbolic languages. The mathematical symbolism was respected just because it was believed to be the key to the operation by which natural forces could be manipulated and nature conquered.

It is interesting to notice that the occult and scientific perspectives coexisted and overlapped in the 16th and 17th centuries when science was in formation and that the magical and religious preconceptions helped to shape the characteristics of science, such as (i) rationalism and empiricism as well as objectivity, which were related with the transcendental character of nature as conceived by Protestant cosmology; (ii) causal reasoning that was based on the idea of the “uniformity of nature”; (iii) mathematical symbolism in its theoretical formulations; and (iv) the will to operate as manifested in its experimental spirit.

Yet, unlike magic and religion, science has its distinctive tools for its undertaking: the understanding and manipulation of the world. Important among them are (i) professional societies and publications; (ii) rational criticism and debates based on a skeptical spirit and a tolerance of differences; (iii) empirical observation and experiments, logic, and mathematics, the systematic use of which leads to distinctive modes of demonstration; and, most importantly, (iv) fruitful metaphors, conceptual schemes, and models, with which theoretical structures the structures and workings of the world can be approached, described, and understood.

A scientific theory must have some empirical statements, in the sense of having falsifiable consequences and hypothetic statements that are not individually falsifiable but are crucial for understanding and explaining phenomena. The hypothetic statements are expressed in theoretical terms: unobservable entities and mechanisms as well as abstract principles. There is no dispute among philosophers of science about the function

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of theoretical terms in a theory as heuristic devices for organizing experiences. What is at issue is their ontological status: Should we take them realistically? For sense data empiricism, the answer is simply negative. But Comte's anathema against the undulatory theory and Mach's opposition to the atom turned out to be grave mistakes. For conventionalism, the foundation of science is much wider than sense data and includes, in addition to logic and mathematics, conventions. In particular, it takes conventional mathematical expressions as foundations of reason to which observables and unobservables are subordinated. But "how real are these constitutive conventions?" is a question to which the conventionalists are reluctant and unable to answer. For internal realism, the reality of theoretical terms is accepted, but only within the theory in which these terms appeared, and cannot be divorced from the theory. The reason is that we have no access to a metaphysical reality if it exists at all. My disagreement with internal realism will be given here and there in the text.

Concerning the ontological status of theoretical terms, the position that I am going to defend in the last chapter is a special version of structural realism. Briefly stated, the position holds that the structural relations (often expressed directly by mathematical structures, but also by models and analogy indirectly) in a successful theory should be taken as real, and the reality of unobservable entities are gradually constituted and, in an ideal situation, finally determined in a unique way by these structural relations.

An immediate objection to this position is that this is a disguised phenomenalism, in which empirical truths of observables are replaced by mathematical truths of observables, and in which there is no room for the reality of unobservables. Critics would argue that the problem of giving an interpretation proves to be much more difficult than just writing out equations that summarize the observed regularities.

To anticipate my arguments in the last chapter, suffice it to point out that in addition to the structural relations for observables, there are structural relations for unobservables, which are more important for understanding and explanation. To the objection that any such structural relation must be ontologically supported by unobservable entities, my answer is that in any interpretation, while structural relations are real in the sense that they are testable, the concept of unobservable entities that are involved in the structural relations always has some conventional elements, and the reality of the entities is constituted by, or derived from, more and more relations in which they are involved. Once we have accepted that unobservable entities are ontologically constituted and epistemologically constructed from real (observable and testable) structural relations, we have more flexibility in accommodating changing interpretations of these entities.

1.2 Metaphysics

Metaphysics, as I understand it, consists of presuppositions about the ultimate structure of the universe. First, it is concerned with the question about what the world is really made of, or what the basic ontology of the world really is. Is the world made of objects, properties, relations, or processes? If we take objects as the basic ontology, then further questions

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follow: What categories of objects are there? Are there mental objects as well as physical objects? What are the basic forms of the physical objects – particle, field, or some other form? In addition, what is the nature of space and time? A difficult question central to ontological discussion is about the criteria of reality, because metaphysicians are always concerned with real or fundamental or primary entities rather than epiphenomena or derivatives. A classical answer to this question by modern philosophers, such as Descartes and Leibniz, is that only a substance is real. A substance exists permanently by itself without the aid of any other substance, and is capable of action without any external cause. Yet, as we shall see, there can be other conceptions of reality, based on the concepts of potentials, structures, or processes instead of substance.

Second, metaphysics is also concerned with principles that govern the nature and behavior of the fundamental entities of the world. For example, there is a principle of identity, which says that individuals should be able to change over time and remain one and the same. Similarly, the principle of continuity says that no discontinuous changes are possible. There are many other metaphysical principles that have played important regulative or heuristic roles in the construction of scientific theories, such as the principles of simplicity, unity, and spatiotemporal visualizability. But the most important among these principles is the principle of causality, which is supposed to dictate the working of nature and helps to make the action of entities intelligible.

Thus, by appealing to ontological assumptions and regulative principles, metaphysics supplies premises and bolsters the plausibility of scientific arguments, and is quite different from empirical, practical, and local statements about observed phenomena and their regularities. Traditionally, metaphysics is highly speculative. That is, its assertions are unexamined presuppositions and are not required to be empirically testable. However, these presuppositions of epistemic and ontic significance are so entrenched in a culture that they appear to scientists as commonsense intuitions. Since these entrenched assumptions give a seemingly plausible picture of the world, and have virtually determined the deep structure of the thinking modes of people who share these assumptions, metaphysics comprises an important part of a culture.

William Whewell once said that

> physical discoverers have differed from barren speculators, not by having no metaphysics in their heads, but by having good metaphysics while their adversaries had bad; and by binding their metaphysics to their physics, instead of keeping the two asunder.
>
> *(Whewell, 1847)*

As we shall see in the text, metaphysical assumptions can be fleshed out with physical parameters. More important than this, however, is that metaphysics provides a comprehensive framework of concepts within which specific theories can be proposed and tested. As is well known, ancient science originally developed from metaphysical speculations. But even now science is still associated with this or that world picture provided by metaphysical ideas. An explanation of a phenomenon is always given in terms of a specific world picture. The question of which ontology, matter, field, energy, or spacetime best explains phenomena is extremely important for a physical theory, far more important than the details of its empirical laws. For example, the empirical content of Newtonian mechanics has been modified only slightly by Einstein's theory of relativity, yet no one would deny that this is a great step in the development of physics, since the old ideas about Euclidean space, absolute time and absolute simultaneity, and action at a distance were swept aside, and the world picture thereby changed.

Examples of the interactions between physics and metaphysics are many. The guidance of the metaphysical assumption, concerning the universality of the principle of relativity, in the evolution from the electromagnetic theory of the 19th century to the special and general theories of relativity is widely acknowledged. On the other hand, developments in physics, particularly in quantum mechanics, quantum field theory, and gauge theory, also have profound metaphysical implications and have radically changed our conception of the physical world, as we shall discuss in the main text. A corollary of mutual penetration between physics and metaphysics is this. Not only is metaphysics indispensable for physical research, but physics has also provided us with a direct access to metaphysical reality. For example, experimental investigations of the Aharonov–Bohm effect and Bell inequality have greatly clarified the ontological status of quantum potentials and the nature of quantum states, respectively, both of which were thought to be inaccessible metaphysical questions. For this reason, Abner Shimony (1978) calls this kind of research experimental metaphysics, emphasizing the important role of physics in testing metaphysical assumptions.

Thus, it is inappropriate to take metaphysics only as an acceptable remainder of scientific theory from which empirical content and logical-mathematical structures have been removed. Rather, it provides scientific theory with a conceptual framework which is endowed with special scientific content. First, it provides a basic model of physical reality so that the theory is intelligible. Second, it prefers certain types of explanation on the basis of certain conceptions of causality. For example, in the case that the mechanical conception of efficient cause is taken as a basis for explanation, this metaphysical assumption has not only determined the hypothetico-deductive structure of physical theory but also entails a built-in reductionist methodology. Moreover, since the positivists are agnostic with respect to causes, and only the realists take causes seriously, the built-in implication of the metaphysical assumption for realism should also not be ignored.

1.3 Causality

The rise of modern science was accompanied with the replacement of authorities or traditions by causes in explaining phenomena. One of the ultimate goals of science is to understand the world, and this is approached by scientific explanation, that is, by finding out causes for various phenomena. According to Aristotle, however, there are different kinds of cause: material, formal, efficient, and final causes. Before the rise of modern science, teleological explanation based on the notion of final cause was a dominant mode of explanation. With the revival of Neoplatonism, Archimedeanism, and atomism in the

Renaissance, there began a transformation in basic assumptions of scientific explanation. Copernicus, Kepler, Galileo, and Descartes, for example, believed that the underlying truth and universal harmony of the world can be perfectly represented by simple and exact mathematical expressions. The mathematization of nature led to a certain degree of popularity of formal cause. But the most popular and most powerful conception of causality, in fighting against the teleological explanation, was a mechanical one based on the notion of efficient cause. Different from final and formal causes, the idea of efficient cause focuses on how the cause is transmitted to the effect, that is, on the mode of this transmission. According to the mechanical view, causality can be reduced to the laws of motion of bodies in space and time, and observable qualitative changes can be explained by purely quantitative changes of unobservable constituting corpuscles.

Mechanical explanation had different variations. According to Descartes, the universe is an extended plenum and no vacuum can exist, any given body is continuously in contact with other bodies, and thus the motion of several parts of the universe can only be communicated to each other by immediate impact or pressure, and no action at a distance would be possible. There is no need to call in the force or attraction of Galileo to account for specific kinds of motion, still less the “active power” of Kepler. All happens in accordance with the regularity, precision, and inevitability of a smoothly running machine. According to Newton, however, force is the causal principle of motion, although force itself has to be defined by the laws of motion. For Newton, as well as for Huygens and Leibniz, the intelligibility of causality was principally lodged in the concept of force. Then a serious question is about the concrete mechanism for transmitting force. This question is so central to the subsequent development of physics that it actually defines the internal logic of the development. The search for a solution to this question has led to the advent of field theory, quantum field theory, and, finally, gauge theory.

There are different forms of mechanical explanation. First, natural phenomena can be explained in terms of the arrangement of particles of matter that are actually involved in the phenomena and in terms of the forces acting among them. In the second form, some mechanical models are adopted to represent phenomena. These models, the so-called toy models, are not necessarily taken as representations of reality but are seen as demonstrating that phenomena can in principle be represented by mechanisms. That is, these mechanical constructions rendered phenomena intelligible. Third, mechanical explanation can also be formulated in the abstract formalism of Lagrangian analytic dynamics. The equations of motion obtained thereby are independent of the details of mechanical systems, but phenomena are nevertheless explained in mechanical terms of mass, energy, and motion, and thus are subsumed under the principles of mechanical explanation involved in the formalism, although they are not represented by a specific visualizable mechanical model.

Among the three forms, the use of models is of special importance. Even the abstract formalism of analytic dynamics needs to be illustrated by models. Moreover, since one of the major motivations in physical investigations is to find out the agent of force at the foundational level when direct causes at the phenomenal level fail to explain, the postulation of models involving hypothetic and unobservable entities and mechanisms is unavoidable. Thus, the necessity of hypothesis is inherent in the very idea of mechanical explanation, or in the search for efficient causes.

Any hypothesis must be consistent with the fundamental laws of nature and with all the generally accepted assumptions about the phenomena in question. But a hypothesis is only justified by its ability, in conjunction with the fundamental laws and general assumptions, to explain phenomena. Thus, its specific content is to be adjusted to permit deduction of statements about the phenomena under investigation. But how can it be possible for a hypothesis about unobservables to be able to explain phenomena? And how can the hypothesis be adjusted so that this goal can be achieved? A tentative answer to these questions, based on the position that I shall argue for in the last chapter, is that only when the structure of a model (any hypothesis is a model), based on analogy drawn from everyday experiences or other scientifically known phenomena, is similar to the structure of the phenomena can a hypothesis fulfill its explanatory function.

The hypothetico-deductive structure of physical theory has immediate metaphysical implications: if a set of mutually consistent hypotheses with a set of unobservable entities serves as causes of the phenomenal world, then it seems undeniable that the hypothetic world gives a true picture of the real world, and the phenomenal world can be reduced to this real world. For example, most mechanical explanations suggest a real world with the hidden ontology of unobservable atoms or elementary particles in motion as the substratum underlying the physical reality. There are other possibilities. For example, Leibniz took the intensive continuum of forces as the metaphysical foundation of phenomena. Other physicists in the 18th and 19th centuries went beyond mechanical explanation but still worked within the general framework of the hypothetico-deductive framework, suggesting different nonmechanical ontologies, such as active principles, fire, energy, and force fields.[3] With each different ontology, physicists offered not only a different physical theory or research programme, but also a different conception of a real world that underlies the phenomenal world.

1.4 Ontology

In contrast with appearances or epiphenomena, and also opposed to mere heuristic and conventional devices, ontology as an irreducible conceptual element in the logical construction of reality is concerned with a real existence, that is, with an autonomous existence without reference to anything external. Since an ontology gives a picture of the world, it serves as a foundation on which a theory can be based. This helps to explain its reductive and constitutive roles in the theoretical structure of science.

Although the term ontology often refers to substance, as in the case of the mechanical world view, in which the basic ontology is particles in motion, this is not necessarily so. The concept of ontology, even in the sense of an ultimately true reality, is wider than that of substance, which in turn is wider than entities and individuals. For example, it can be argued, as the Neoplatonists like Kepler would do, that mathematical relations, as they represent the structure of the universe, are the foundations of reality; even forces, as the causal principle, have to be defined in terms of mathematical relations. While it can be argued that any mathematical structure has to be supported by physical relations between entities, from a constitutive perspective, a physical entity – if it is not merely an empty name – can only be defined by the relations in which it is involved. This is only one example of what Cassirer calls the "functional mode of representing reality." Another example can be found in Whitehead's philosophy of process. According to Whitehead, activity-functioning is not a function of a changeless underlying stuff; rather, a physical object is a connection, a more or less permanent pattern of the basic functioning. He argues that nature is a structure of evolving processes, the reality is the processes, and the substantial things issue out of the process of activity and becoming, which is more fundamental than the things.

This is, of course, a very controversial topic. According to Julius Mayer, who follows Leibniz in taking forces as the primary agency of nature, forces, as the embodiment of nature's activity, should be viewed as nonmechanical yet substantial entities. And for Meyerson, entity is essential to explanation and should not be dissolved in relations or processes. More importantly, a historical fact is that the notion of ontology is almost always connected with that of substance. This connection constitutes an underpinning in the discourse of physical sciences and cannot be passed over in the examination of the foundations of physics.

Then what is substance? Substance is always characterized by a constellation of primary and essential qualities. These qualities exist in space and time and are conserved in the changes of their spatial locations and temporal moments, and to these all other qualities can be reduced. Since in scientific discourses the nature of reality can only be discussed in terms of its symbolic representations, ontology in general, and substance in particular, as a symbolic model of reality, is a piece of science itself and cannot be separated from science. Thus, the understanding of what are the primary qualities is different in different theories, and each theory determines its own kind of substance. However, a generally shared assumption, since the time of Leibniz, holds that substance must be fundamental (in contrast with epiphenomena), active or the source of activity, and self-subsistent, meaning that the existence of substance is not dependent upon the existence of anything else. One of the main conclusions of this book is that a conceptual revolution generally turns a previous substance into an epiphenomenon, and thus changes our conception of what is the basic ontology of the world.

In classical physics, Descartes took space or extension as substance. Newton's case was much more complicated. In addition to substance, his ontology also included force and space. And his substance referred not only to passive material particles, but also to the active ether. For Leibniz, substance was a center of primitive activity. This activity was not the manifestation of a stuff or matter, but the activity itself was the substance, and matter was an appearance on the surface of this activity.

The dominant view after Leibniz was to take substance as inherently active objects, usually divided into different ontological categories: discrete individuals (such as visible massive particles and invisible atoms) and continuous plenum (such as the Cartesian

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extension and the classical field). An individual is a spatially bounded object and at least has some other properties. It is usually characterized as what can be identified, re-identified, and distinguished from other members of its domain.[4] Here identity is ensured by the conservation of essential qualities, and distinguishability has its origin in impenetrability, which presupposes a spatial bound of the object. The concept of individual is usually connected to that of particle because both have to be discrete, but it is narrower than the latter owing to its requirements of distinguishability and impenetrability. In quantum theory, quantal particles are identifiable but neither re-identifiable nor distinguishable from their like. They are thus not individuals but can still be accounted as particles mainly because of the conservation of rest-mass, charge, and spin.

This is one example of the theory dependence of our conception of substance. Another interesting example is that of the ontological status of energy. Traditionally, energy was thought to be one of the most important features of substance since it indicated that its carrier was active, and, as the measure of ability to act, it was conserved. However, as a measurable property rather than a self-subsistent object, energy itself was usually not to be regarded as substance. For example, when Carl Neumann claimed that potential energy was primary and able to propagate by itself, Maxwell maintained that energy could only exist in connection with material substance.[5] For the same reason, energeticism, according to which energy as pure activity is the basis of physical reality, was usually accused of being phenomenalism because of its rejection of substance. Yet it can be interpreted otherwise. What if energy is taken as substance with the new feature of being always active, always changing its form while keeping its quantity constant? Then energeticism would seem to be a precursor of James's functionalism and Whitehead's ontology of process.

These two examples suggest that an ontological assumption is fundamental not only to a specific theory but also to a research programme. Let us have a closer look, from this perspective, at the genesis of the field theory programme. The electromagnetic field was taken to be responsible for continuously transmitting electromagnetic force through space. The substantiality of the field in 19th century physics is a subject for debate. Sometimes it is argued that Maxwell established the substantiality of the field because he proved the presence of energy in the field. But this claim is questionable. For Maxwell, the field was not an object but merely a state of the mechanical ether that obeyed Newton's laws of motion. This means that for Maxwell the field was not self-subsistent and hence could not be substantial. What the presence of energy in the field established was just the substantiality of the ether rather than that of the field.

Sometimes it is also argued that the removal of the mechanical ether entails the removal of the substantiality of the field, and this thereby supports the claim that spacetime points are the basic ontology of field theory.[6] In my opinion, however, it is precisely the removal of the mechanical ether that establishes the nonmaterial substantiality of the field. The reason for this is that, in this case, the field becomes the only possible repository of the field energy, and the field energy presupposes a substance as its repository. As to spacetime points, the reason why they cannot be viewed as the basic ontology of field theories is that