

Part IV
Philosophy of Nature

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Hegel and the Sciences

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1. Introductory Remarks

When dealing with Hegel's *Philosophy of Nature* and in particular with the sections of his *Encyclopaedia* entitled "Mechanics" and "Physics," it is virtually impossible to ignore the harsh criticism that this part of his system has faced over the past two centuries. Hegel was fully aware of the opposition faced by idealist philosophy of nature (especially in the latter's Schellingian form), even though this opposition had by no means reached its zenith in the first quarter of the nineteenth century. In the Addition to §244 of the *Encyclopaedia* of 1830, we find the following statement:

It may certainly be accepted as *indisputably* true ... that the *philosophy of nature* in particular is suffering from a very considerable lack of favour. ... [L]ooking at the way in which the *Idea of the philosophy of nature* has exhibited itself in recent times, one might say that in the first gratification which its discovery has afforded, it has been grasped by fumbling hands instead of being wooed by active reason, and that it is by its suitors rather than by its detractors that it has been done to death.¹

It is likely, however, that Hegel did not expect scientists and philosophers to condemn his own version of *Naturphilosophie*, soon after his death, as an example of "an external formalism," of "a notionless instrument for superficiality of thought and unbridled powers of imagination,"² much in the way he had criticized the philosophies of nature produced by Schelling and, especially, Schelling's followers. Yet this condemnation is exactly what ensued.³ One example may suffice to demonstrate the extremely negative attitude toward all philosophy of nature that prevailed just a decade after Hegel's death. In 1842, the mere remark that "this is philosophy of nature" was enough to motivate

A Companion to Hegel, First Edition. Edited by Stephen Houlgate and Michael Baur.
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Johann Christian Poggendorff (1796–1877) to reject studies by Robert J. Mayer (1814–1878) and later by Hermann von Helmholtz (1821–1894) on the principle of energy conservation and to refuse their publication in the renowned *Annalen der Physik*.⁴

James Hutchison Stirling (1820–1909), one of the first apologists for Hegel in Great Britain, has given quite an accurate description of the impression Hegel's *Philosophy of Nature* may leave on the impartial reader who is unfamiliar with Hegel's distinctive terminology:

I have before me not an active, sensible, intelligent man, with his wits about him, looking at *the thing* in a business-like manner, and treating it so on the common stage of education and intelligence as it is now, but an out-of-the-way sort of body, a mooning creature with a craze, who, in pure ignorance, non-knowledge, non-education, non-intelligence, simply impregnates a mist of his own with confused figures of his own, that have no earthly application to the business in hand – as a Jacob Böhm[e] or other mere stupid dreamer might do. That any reputable persons of the usual education and position, should be caught with such self-evident, gratuitous, muddle-headed nonsense, fills me with ... surprise, regret, sorrow. ...⁵

Though he is, of course, being ironic, Stirling is referring to certain passages from Hegel's paragraphs on the solar system, which William Whewell (1794–1866), in an essay from 1849, had argued were indeed nonsensical.⁶ Whewell had done this, as Stirling rightly observes, on the basis of his own, very inadequate translations of selected paragraphs of the Hegelian *Encyclopaedia*.

Generally speaking, Hegel's *Philosophy of Nature* – much more than most great books in the history of Western thought – has been the subject of a lively debate as to whether it makes sense at all.⁷ How can this be explained? Why did Hegel's *Philosophy of Nature* (especially his “Mechanics” and “Physics”) attain this strange position in human history, characterized by such a gulf between its apologists and its detractors?

Those who consider Hegel's “Mechanics” and “Physics” to be an insignificant aberration of the human mind perceive Hegel to be a philosopher who does not accord due respect to the wealth of knowledge that is based on physico-chemical experiments and astronomical observations; they argue that Hegel generally did not care much about scientific insights that had been or must be obtained a posteriori. One of the historical roots of this perception is to be found in Hegel's early work, written to obtain the *venia legendi* at the University of Jena in 1801: the *Dissertatio philosophica de orbitis planetarum*. At the end of this short book, Hegel had famously dared to question the hypothesis that a planet was “missing” between Mars and Jupiter. As any modern reader, working with some diligence, can verify by reading the original Latin text, *De orbitis planetarum* does not contain any a priori judgment stating that no planet or celestial body, revolving about the sun between Mars and Jupiter, can possibly exist. Rather, Hegel formulates a careful if-clause, saying that *if* a series based on the numbers proposed by Plato in his *Timaios*⁸ somehow reflects the true order of the planetary orbits, *then* there is no need to look for a planet between Mars and Jupiter.⁹ As Craig and Hoskin¹⁰ have pointed out, there is hardly anything outrageous in this statement, and it was certainly not meant as an a priori proof of the nonexistence of the minor planets,

which, starting precisely in 1801, were discovered by Giuseppe Piazzi (1746–1826) and other astronomers to be orbiting the Sun between Mars and Jupiter. Nevertheless, researchers such as Franz Xaver von Zach (1754–1832) and Matthias Jakob Schleiden (1804–1881) claimed that Hegel had “dialectically annihilated” the minor planets.¹¹ Since there are many examples of similar judgments by scientists as well as philosophers, it is not at all astonishing that corresponding prejudices against the author of *De orbitis planetarum* (and later of the *Encyclopaedia*) became very common among scholars of all disciplines and the general public.

But the myth of the dialectically annihilated asteroids, influential though it was, would not have been sufficient to establish so deeply rooted an aversion to Hegel’s philosophy of nature as the one that actually emerged. There had to be a *more substantial* point to Hegel’s (and partly also to Schelling’s) philosophy that provoked the resistance of so many erudite minds. There had to be some Hegelian standpoint or starting point that significantly distinguished his philosophy from Kant’s: for, throughout the nineteenth century, the latter was respected by at least a very significant number of scientists. Why was Kant respected? Probably because Kant, famously stating that conceptions without intuitions were empty *seemed to limit* the range of justified philosophical ‘constructions’ *much more strictly* than Schelling and Hegel did after him. John Burbidge explains the underlying problem concisely:

Any philosophy of nature has a fundamental problem: How can the thinking of philosophy do justice to the facts of experience? Kant presented the challenge in a definitive way: thought involves concepts, and concepts, being general, express only possibilities. In sensation we encounter facts, and facts are singular and actual. ... [W]here thought follows its own logic it can construct consistent theories, but these have no truth unless one can show how concept and fact correspond. In other words, explanations of nature are impossible without some point of contact between thought and ... experience.¹²

Even though Hegel did indeed largely recognize the latter point in his philosophy of nature,¹³ many of his opponents pretended that he did not. While Hegel, in his own eyes, aimed at a philosophy that is *to a degree* a priori but also close to what he considers to be concrete phenomenal reality, his critics perceive his system – especially in his discussion of subjects that are also treated by the empirical sciences – to be *much more thoroughly* a priori than Kant’s and much more abstract. This may be due to a specific aspect of Hegelian thinking that Burbidge, again, characterizes thus:

philosophical thought, following the cognitive demands of the logic [i.e., Hegel’s *Science of Logic*], could construct a model to represent the basic organization of matter, and then show how natural processes reproduced this conceptual structure. In other words ... , the idea could derive natural principles by means of pure thought and then confirm its conclusions with reference to what actually happened in nature. This derivation using construction and proof would lead to a genuine cognition of nature.¹⁴

It is this very question of how to get from “pure thought” to “what actually happens in nature” that lies at the heart of many attacks against Hegel and his followers. The standard argument against Hegel – illustrated above by the “dialectically annihilated

asteroids” – is that he intended to *derive* the structure of space, time, motion, matter, of the properties of light, electricity, magnetism, chemical elements, the essence of organisms (eventually including human beings, their history, etc.), *completely and utterly from pure reason*, referring to empirical data where they somehow matched his ideas, but ignoring them where they did not. This immediately leads to the question of how Hegel *really* derives the basic terms and concepts of his philosophy of nature.

2. The ‘Construction Principles’ of Hegel’s Philosophy of Nature

The opening paragraphs of the second section of the philosophy of nature, entitled “Physics,” provide important hints as to how any philosophy of nature should derive its basic terms. In the remark to §276, which deals with light, Hegel states: “that which is immanently philosophical is the inherent necessity of [the] *Conceptual determination*, which then has to be illustrated by *some* natural existence *or other*.”¹⁵ In the same sense, the addition to §275 begins thus: “The a priori *Conceptual determination* of light is now the *primary* consideration. In the second instance we have to discover the mode and manner in which this conceptual determination occurs in our sensuous perception.”¹⁶ These phrases may seem hardly intelligible without illustration. Consider the conceptual determination of light. Light, says Hegel in the main text of §275, is “*pure self-identity*, unity of *intro-reflection* [*reine Identität mit sich, als Einheit der Reflexion-in-sich*].”¹⁷ Now even this concrete example of a ‘conceptual determination’ may still appear enigmatic. It becomes more transparent when we add the following phrases from the addition to §274:

We enter logically into the sphere of essence. This is a return into self in its other; its determinations appear within each other, and intro-reflected in this way, now develop as forms. These forms are identity, diversity, opposition, and ground [*Identität, Verschiedenheit, Gegensatz, Grund*]. This is therefore an advance upon the primary immediacy of matter.¹⁸

Taken together, this means that *light* – the first phenomenon considered in the *second* section of Hegel’s philosophy of nature, “Physics” – corresponds conceptually to the category of *self-identity*. Accordingly, then, all phenomena treated in “Physics” correspond to categories developed in the sphere of *essence*, that is, in the second section of the *Science of Logic*. Much in the same way, Hegel had pointed out in the first section of his *Philosophy of Nature* that time is “intuited becoming,”¹⁹ that is, that there is a correspondence between the category of *becoming* and the phenomenon occurring “in our sensuous perception” as *time*. As a first approximation, it may thus be said that all categories developed in the *Science of Logic* have their respective counterparts in the *Philosophy of Nature* (and also in the *Philosophy of Spirit*); moreover, the succession of the logical categories and of their respective counterparts is roughly the same. On closer examination, however, we find subtle differences between content, structure, and the arrangement of the categories developed, respectively, in the *Science of Logic* and in the two subsequent parts of Hegel’s system;²⁰ but such a closer examination would lead too far astray here. Suffice it to say that without any such differences, the *Philosophy of Nature* would be nothing but an unnecessary repetition of the *Logic*.

The basic point in the present context is that the following two-step construction scheme seems to underlie Hegel's *Philosophy of Nature*.

1. The basic conceptual content of the *Philosophy of Nature* is derived from the categories developed in the *Science of Logic*, under the 'boundary condition' that nature is "the Idea in the form of otherness" or "externality."²¹

2. Hegel makes numerous and ubiquitous references to the sciences and to common-sense-perception of natural phenomena. They are to be understood – in the light of §§246, 275, and §276 of the *Encyclopaedia* – as (mere) illustrations of the way "in which the conceptual determinations occur empirically."

Though these two points may give the impression that Hegel – largely in the way referred to in the Introductory remarks above – aims at an *entirely* a priori and hence "nonempirical" account of all natural phenomena, this is not true for the following reasons.

(a) As Carl Siegel rightly observes, a priori knowledge – as conceived by Schelling and also by Hegel – does not preclude reference to experience: as Siegel puts it, Schelling's and Hegel's a priori is nothing other than *conceptual necessity*.²² What does 'conceptual necessity' mean, according to Hegel? We may call a natural law conceptually necessary in the Hegelian sense if it reveals a structure or a relationship of concepts that corresponds to the basic principles of the *Science of Logic*. For example, the existence of natural motions is conceptually necessary in the sense that motion represents the unity of space and time that is derived dialectically at the start of the *Philosophy of Nature* in accordance with the development at the start of *Logic of Being*. That motion is the unity of space and time is evident from the fact that velocity – the basic quantity characterizing motion – is a relation between the length of a path and a corresponding duration. Within "Organics," Hegel argues that it is conceptually necessary that (higher) animals do not eat all the time – or that they have, as he puts it, "interrupted intussusception": their nonpermanent eating corresponds to their individualized, or rather self-individualizing, relation with individuals and with inorganic nature. This contrasts with the behavior of plants that nourish themselves (if possible) without break and that do not yet represent fully individualized organisms.

The analysis of Kepler's laws in §270 of the *Encyclopaedia* provides another, much more intricate example. Hegel starts by arguing that space and time have to be considered as two qualitatively distinct moments of planetary motions. Kepler's third law – which states that the squares of the orbital periods of any two planets are proportional to the cubes of their distances from the sun – is the mathematical formulation of the particular (quantitative and qualitative) relation between space and time in the case of planetary motion. Concerning the "conceptual necessity" of elliptical orbits, Hegel's reasoning is this: Since we know (a posteriori from Kepler's third law) that space and time are not merely exchangeable parameters in celestial motions (as they are, e.g., in unaccelerated rectilinear motion: $s = \text{const.} \cdot t$, $t = s / \text{const.}$), it would not fit the level of complexity reached in celestial mechanics to conceive the planetary orbits as circular, since a circle is defined by one and only one quantity, namely its radius, and in the mathematical description of the motion of a body on a *circular* orbit the spatial coordinate (e.g., the position angle ϕ) and time coordinate t are precisely exchangeable parameters, linked with each other again by a simple linear function: $\phi = \text{const.} \cdot t$. So the geometrical description of circular motion as $\phi = \text{const.} \cdot t$ would be largely the

same as that of rectilinear motion (cf. above). Only if the speed of a body on a circular orbit were periodically to increase and decrease, would the situation be different. As for this possibility, however, Hegel holds that, even though “it is ... conceivable ... that a uniformly increasing and decreasing motion should take place in a circle,” this conceivability is only an “*abstract representability*,” since there is no reason why the speed of a body moving along a line that is completely isotropic should increase and decrease at specific, but geometrically equivalent points of its orbit. (The term “abstract representability” (*abstrakte Vorstellbarkeit*) is the Hegelian opposite of conceptual necessity.) Only in the case of an *elliptical* orbit do space and time cease to be merely exchangeable parameters, because here the function describing the time-dependence of the radius vector of a planet is a complex nonlinear equation (Kepler’s equation) that cannot be inverted in any analytic way. Hence, for the motion of a planet along an elliptical orbit, space and time are no longer exchangeable parameters. In this sense, the elliptical orbits of the planets (described in Kepler’s first law) are conceptually necessary in the light of the totality of Kepler’s laws. This highly complex example illustrates that Hegelian conceptual necessity is closely linked to systematical coherence (namely of a set of basic laws, logical structures, or metaphysical assumptions).

It is important to note with respect to the above examples that we do not have to find Hegel’s analysis entirely convincing in order to see what Hegel means *formally* by conceptual necessity. More specifically, the point to be made about conceptual necessity is mainly that it does not preclude reference to experience. On the contrary, conceptual necessity “justifies” the content of empirical laws or observations; it is their “rationalization” by means of dialectics.

(b) As far as the *details* of natural phenomena are concerned, Hegel does *not* claim that philosophy should aim at deriving all of them a priori, that is, at proving that all natural phenomena necessarily present themselves in the way they do. In several passages (e.g., the end of the extensive addition to §270), Hegel expressly states that it is impossible for a philosophy of nature to account for all the details of natural processes and phenomena.²³ The same skepticism toward a complete a priori deduction within the domain that has traditionally been called *ontologia specialis*²⁴ occurs in the Preface to the *Philosophy of Right*, where Hegel criticizes Plato and Fichte for their ambition to demonstrate the necessity of particular positive laws, social institutions, and so on – an ambition that he calls “super-erudition” (*Ultraweisheit*).²⁵

The property of nature that makes it impossible for spirit to comprehend everything in it as necessary or to derive all its features even has a well-known proper name in Hegel’s system: it is called “the impotence of nature” (*die Ohnmacht der Natur*).²⁶ This term reflects the fact that any – even the most sophisticated – system of classification of natural genera and species, as well as any attempt to find basic forces, pure substances, and so on – in short, each and every systematization of nature – is confronted with transitional phenomena, borderline cases, and exceptions that do not occur in pure logic. Hegel fully acknowledges this:

This impotence on the part of nature sets limits to philosophy, and it is the height of pointlessness to demand of the Concept that it should explain, and as it is said, construe or deduce these contingent products of nature, although the more isolated and trifling they are the easier the task appears to be.²⁷

In other words, Hegel does recognize that contingency or chance plays an essential role in the realm of nature, and he holds that philosophy should, for this very reason, refrain from any attempt to deduce *all* features of the material world from a priori principles.

It is, however, still a matter of debate whether the “impotence of nature” – together with the limitations of our knowledge about nature at any given time – inhibits an a priori conceptual account of nature *altogether* or merely limits it. It seems to me that the second option, according to which at least the “structure or skeleton of the *Philosophy of Nature* is developed purely conceptually,”²⁸ is more likely to describe what Hegel actually does.²⁹ Nevertheless, it may be that any present-day philosophy of nature should go one step further, in a direction only foreshadowed but not fully realized by Hegel: “to provide [only] a flexible framework which organizes in an intelligible way, and is wholly *relative* to, the scientific knowledge of a given time, and which changes with future scientific discoveries” – as Houlgate puts it.³⁰

3. The Content of Hegel’s “Mechanics” and “Physics” in Outline³¹

Although a wealth of secondary literature on Hegel’s “Mechanics” and (to a lesser extent) on his “Physics” has been published especially since 1970, texts giving an *overview* of these sections’ contents are still rare. The aim of the present section is to fill this gap and to pave the way for a discussion of selected problems (Section 4).

3.a. “Mechanics”

It has been mentioned above that *externality* (*Äußerlichkeit*) – or, as Hegel sometimes puts it, *extrinsicity* (*das Außereinander*) – represents the *basic conceptual element* – we could also say, the boundary condition – under which everything in nature exists.

The first concept we encounter in the *Philosophy of Nature*, *space*, is nothing other than the immediate realization of nature’s basic determinateness. This also is stated in a passage from Hegel’s *Lectures on the Philosophy of Spirit*:

All that is natural is spatial, time already being higher, already initiating inwardness; spatiality is nothing other than something extrinsic, everything having place in space, where everything is affirmative, determinate, and does not interfere with anything else. Space is the subsisting of all things, where each is indifferent to the others. This is the abstract absolute determinateness of nature, extrinsicity.³²

This passage presents two insights at once. The first is that spatiality, *qua* basic element of any natural existence, is externality, and that externality means, initially, a mode of mere *coexistence* in which nothing “interfere(s) with anything else.” The second insight – only implicitly contained in the above lines – is that *time* is fundamentally different from space. By *not* being a mode of mere coexistence, time is the “now” that *excludes* any other “now,” in contrast to space, which in its immediacy is the “here” that *does not interfere* with other “heres.”

While we are used to speaking of them as merely two *different* concepts, or *different* coordinates – the spatial coordinates x, y, z versus the time coordinate t – Hegel makes clear at the beginning of his “Mechanics” that it is not satisfying philosophically merely to distinguish these concepts without asking about their *relation* to each other.³³ When asking about this relation, we find that space is on the verge of the *transition* into time. This can be seen by considering the infinitesimal element of space: the point. The point is the negation of space, more precisely of spatial extension. But it is more than that. The point is intuited negativity, the intuited exclusion of others (other points). As such, it is *in nuce* what the *moment* of time is in a more concrete way. Hence it makes sense to claim that there is a transition from space to time, and to illustrate this transition with the concept of the (geometrical) point. Conversely, there is also a ‘transition’ from time to space. Time becoming spatial is *motion*. While time is a sequence of “now, now, now,” motion is a sequence of the form “now here, then there, then there.” Motion, as Hegel puts it, is the unity of space and time, posited in the logical form of time (i.e., in a negative form). Alternatively, motion may be called the unity of space and time in an ‘ideal’ form, because motion is something immaterial (even though moving objects are not immaterial). Matter, by contrast, is the unity of space and time posited in the logical form of space (i.e., in a positive form or in a ‘real’ form).³⁴ By reference to the law of conservation of momentum ($p_{\text{total}} = \sum m_i v_i = \text{const.}$), Hegel tries to show that mass (the basic quantitative unit of matter) and velocity (the basic quantitative unit of motion) have the same effect and must therefore be closely related conceptually: a piece of matter, hitting another one that has twice its mass, will, if it is thereby brought to rest in an elastic collision, transfer only half of its velocity to the second one. Also due to the same law of conservation of momentum – or, as Hegel would say, due to the exchangeability of the factors ‘mass’ and ‘velocity’ – a mass of 6 pounds traveling at ‘speed 4’ has the same impact on another object as a mass of 8 pounds traveling at ‘speed 3.’³⁵

With this example, we have already entered the second section of “Mechanics,” entitled “Finite Mechanics.” This section treats *inert matter* as subject to different kinds of *motion* that cannot be sustained for long, but come to an end: *impact* and *free fall*.³⁶ Of course, according to classical mechanics, cases are conceivable in which an impact gives rise to a rectilinear motion that does *not* come to an end in time – namely in the case of the absence of any friction or forces acting at a distance. However, Hegel considers this case of infinite, unaccelerated rectilinear motion to be an empty abstraction (and indeed, such a motion does not occur on Earth). Impact and fall, in the way we encounter them in terrestrial nature, constitute “finite” – first of all in the sense of temporally limited – processes. Moreover, they require for their realization initial conditions that are contingent and extrinsic to the moving bodies themselves (in many textbook cases, these initial conditions are artificially produced). The free fall of a body, for instance, requires its being elevated to the starting point of fall, and this is a merely external and contingent condition.

The subject of what Hegel calls “Absolute Mechanics” is the motion of celestial bodies – more specifically, the motion of bodies in a solar system. Why does Hegel make the motions of celestial bodies a wholly distinct *stage* of his “Mechanics,” instead of considering them merely as motions in a field of force under specific boundary conditions, as is done in classical mechanics? First, because the motions of bodies in

the solar system appear as temporally infinite (at least on time scales accessible to us). This infinity is, according to Hegel, more than a result of the boundary condition ‘absence of friction,’ since it is also connected with *forms* of motions that are entirely different from terrestrial ones, that is, from ones in which friction generally plays a dominant role. Phenomenally, there is a significant difference between natural motions observed under terrestrial conditions and the motions of the planets. The motions of bodies in the solar system appear to us as self-sustaining infinite motions. They proceed along closed orbits that are described mathematically (to close approximation) by conic sections and have an exact periodicity over extremely long times – a fact that contributed to establishing astronomy as a science very early in human history. This phenomenal and epistemological distinction between celestial and terrestrial natural motions is reflected in Hegel’s distinction between “finite” and “absolute” mechanics.

With respect to the categories developed in the *Logic of Being*, Hegel observes that matter becomes “qualified matter” in being considered as a system of internal relations. The qualification, however, lies so far just in the different forms of motion, or, as John Burbidge puts it: “mechanics talks about how movement [we may add: and *only* movement] particularizes matter.”³⁷ The qualification thus remains relatively extrinsic to the members of the solar system themselves; the Sun, for example, does not by itself exhibit any essential relation to all the bodies revolving around it. The categorial development – the main driving force of the philosophy of nature – must hence proceed to a kind of qualification that does not just consist in distinct shapes of trajectories of ‘mass points.’ It must proceed to a sphere where every individual part of a considered whole *shows* its being related *to* the whole. As Hegel puts it: “what the solar system is as a whole, is what matter has to become in particular.”³⁸

3.b. “Physics” and the Transition to “Organics”

The subject of *Physics* is matter that is about to find its individual form: “Bodies are now subject to the power of individuality.”³⁹ Mechanical matter (matter as it is considered in Hegel’s “Mechanics,” but also in the corresponding parts of modern textbooks on classical mechanics) is not yet individuated since among its many (qualitative and quantitative) properties, only its mass, velocity, acceleration, and so on come into play. This is also why within large parts of classical mechanics, material entities can be considered as *point masses*. Only their *ways of motion* with respect to other bodies are relevant. By contrast, what we are confronted with in the second section of the *Philosophy of Nature* is the *process* by which bodies strive for individuation and “qualification,” strive to be constituted as qualitatively specific entities, with their qualities lying in themselves, not in their motion.⁴⁰

3.b.1

In its immediacy, material individuality manifests itself as *light* and *dark*. Light itself is but the simplest *universal* quality of nature; Hegel calls it the “abstract self of matter.”⁴¹ As mentioned above in Section 2, light is also paralleled with the logical category of

pure *self-identity*.⁴² When light actually takes the form of an individual material body, it appears as the Sun, or, more generally speaking, as a star. Hegel introduces a slight categorial difference between the Sun and the stars. While the concept of a star is light as an individual natural body (in its mere immediacy), the concept of the Sun is the star as “moment of a totality” (i.e., of a solar system; §275).⁴³

On the basis of his *Logic of the Concept*, Hegel distinguishes four moments of the solar system: the *Sun* (corresponding to the notion of universality), the dependent “bodies of opposition” (*satellites* and *comets*) (corresponding to particularity), and the *planets*, which, by virtue of their being individual subcenters of motions, correspond to concrete singularity. The idea that particularity has *two* counterparts in the solar system – satellites and comets – has its root in Hegel’s conviction that nature is the sphere of difference or otherness. In Hegel’s words: “The second term [i.e., particularity] ... appears in nature as a duality, for in nature the other must exist itself as an otherness.”⁴⁴

Our paradigm of a planet is the Earth. From §280 on – after the further discussion of the solar system within “Physics” – Hegel’s *Philosophy of Nature* is devoted to terrestrial nature.⁴⁵ This is to some extent a vestige of the historical development of Hegel’s thought, since in the fragmentary systems developed up to 1804/1805 in Jena, Hegel seems to have divided the *Philosophy of Nature* mainly into the “Solar System” and the “Terrestrial System,”⁴⁶ still corresponding to the Aristotelian distinction between supralunar and sublunar worlds.

On Earth, what the ancients already recognized as the basic conceptual moments of inorganic nature are the four elements. They are also called “physical elements” in the *Encyclopaedia*. The four “physical” elements are, famously, air, fire, water, and earth. Hegel calls the physical elements “universal natural existences, which are no longer independent, and yet are still not individualized.”⁴⁷ He is fully aware of the fact that already during his time “[n]o educated person, and certainly no physicist or chemist is ... permitted, under any circumstances, to mention the four elements.”⁴⁸ However, he holds that these do represent a necessary, basic stage of the concept of nature, prior to the more sophisticated system of the *chemical* elements.⁴⁹ The irreducible function of the four elements, according to Hegel, lies in their being moments of the “becoming of the universal individual” – the Earth.⁵⁰ (The question of how this may be translated into present-day philosophy will be briefly discussed below.)

Air again represents the moment of universality (as light does in the previous sphere); in the context of matter’s striving for individuality, air is a negative moment: it is “negative universality against the specific” and has the power of dissolving the latter, as becomes evident for example from wind-supported erosion processes and various chemical processes supported by the presence of air.⁵¹ Fire and water, by contrast, represent the moment of particularity within the physical elements. *Fire* can be said to radicalize the shape-dissolving power of air: it is “the consumption of another which simultaneously consumes itself.”⁵² With respect to *water*, Hegel stresses the dissolving power that it has as well, but he emphasizes even more its “neutral” character and its “shapelessness,” which is its capacity to take on any shape.⁵³ *Earth* or “terrestrialness” (*Erdigkeit*) represents the moment of singularity. It is the concretized “concept of individuality,”⁵⁴ or, as Hegel puts it in a manuscript from his Jena period: “Earth, as the reduction of the elements, stands in a passive relationship to itself, and is therefore determinateness in itself.”⁵⁵

Instead of speaking of four physical elements, it might be better to speak – given the background of nineteenth- and twentieth-century physics – of the four basic aggregate states of matter: the gaseous, plasma, liquid, and solid states. It might be said, furthermore, that the gaseous, liquid, and solid states are more abstract ‘versions’ of air, water, and earth, respectively. The correspondence between fire and the plasma state of matter is more difficult to show.⁵⁶ But recalling that the four elements were introduced by Hegel as moments of the becoming of the universal individual (the Earth) strengthens the case for the aggregate states, since we know today that planet formation does indeed involve phase transitions from the gaseous to the liquid, solid, and plasma states of matter.

Returning to Hegel’s “Physics,” its first section concludes with the meteorological process. It is understood by Hegel as a process of the four physical elements, which are in its course perpetually transformed into one another. *Process* here turns out to be more fundamental than any self-contained subsistence. However, Hegel goes too far in holding that water, for example, is not conserved materially in the process of evaporation, but wholly *transformed* into the element air. It could, of course, be said of the *aggregate states* that the one is completely transformed into the other, but this cannot be said of the *substance* (namely, water) that is subjected to the process of evaporation. I shall come back to this problem below in Section 4.b.

3.b.2

In the second section of Physics, entitled “Physics of Particular Individuality,” Hegel treats specific gravity, cohesion, sound, and heat. This section is best understood by taking a closer look at its last stage. The conceptual determination of *heat* is “matter’s restoration ... to formlessness.”⁵⁷ Heat thus clearly represents a negative moment of the process of matter’s (self-)formation. This negative moment – which has its counterpart in the second law of thermodynamics (not yet known to Hegel, of course)⁵⁸ – paves the way for a more than merely mechanical individualization of natural bodies. Phenomenologically, the “negativity” of heat – as well as of sound – appears in their generating *internal vibrations* of bodies that may lead to their disaggregation.

Hegel’s concept of heat is in remarkable accordance with the kinetic theory of gases, developed in nineteenth-century physics, insofar as both are based on the conviction that “heat is simply a *modal condition* of matter.”⁵⁹ This wording anticipates similar ones that we are used to finding in physics textbooks only since the second half of the nineteenth century, that is, since Maxwell. In Hegel’s own lifetime, by contrast, most scientists still viewed heat as a particular substance (the so-called *caloric*).⁶⁰

3.b.3

In the third section of Physics, entitled “Physics of Total Individuality,” form becomes immanent to matter in a way that no longer depends on gravity. The first concept that we encounter in this section is *shape*, which appears as “spatial assemblage of material being” or as external spatial limitation of bodies.⁶¹ Most strikingly, shape manifests itself in nature in the formation of crystals (though, of course, noncrystalline objects in nature also have shape). “The form which deploys itself in crystallization,” says Hegel, “is a mute vitality, which is active in a truly remarkable way within that which

is purely mechanical."⁶² This is not to say that crystals were little organisms; but in crystallization and crystal growth, matter *tends* toward a specific shape – depending on its chemical composition and other factors – and hence teleological categories do come into play here.⁶³

Magnetism, which we have become accustomed to consider as an epiphenomenon of electric currents, is also treated as a phenomenon related to shape in Hegelian physics. The characteristic feature of magnetism is polarity, where the poles do not have any subsistence of their own.⁶⁴ Magnetic polarity is even *defined* as a relation between two indivisible entities that cannot be separated from each other – at least not without splitting up again into poles. It still holds true for contemporary physics that no magnetic monopoles have been found.

In *electricity* we are confronted with a different kind of polarity, namely one that is characterized by the relative subsistence of the respective poles.⁶⁵ This relative subsistence of the electric poles corresponds to the existence of bodies (as well as ions and elementary particles) with positive and negative electrical charges. Terms such as “anions” and “cations” or – much earlier in the history of physics – “resinous electricity” and “vitreous electricity” – have been coined to account for the duality of electrical charges. At the same time, electricity is more of a *process* than magnetism, whence Hegel speaks of the “electric movement” (*das elektrische Bewegen*) that is able to neutralize differences as well as to create them, or, in logical terms, to posit as identical the differentiated as well as to differentiate the identical.⁶⁶

Electricity finally passes into the *chemical process*. Under the heading of “chemism,” the latter figures also as an important section of the *Science of Logic*. There it is considered in the middle section of the *Logic of the Concept*, namely as one of the three forms of “objectivity,” which are mechanism, chemism, and teleology. Even though “chemism” as treated in the *Science of Logic* is not identical with the “chemical process” as analyzed in the *Philosophy of Nature*, the very fact that Hegel names the whole second sphere of objectivity in the Logic “chemism” points to its outstanding significance, in marked contrast to Kant’s neglect of chemism in comparison with mechanism and organism. Generally, the relations between objects in Hegelian chemism can be characterized in the following way: objects that differ chemically have their respective essential characters expressly and only by virtue of their *difference* from each other, and are driven by the absolute urge to merge and reach a neutral unity thereby.⁶⁷ Within Hegelian “Physics,” the chemical process is the point of culmination of the categorial development. By virtue of the drive to integrate opposite substances into a whole, the chemical process already has a structure that is analogous to life; if it were able to rekindle and reproduce itself after having come to its end, it could in fact be said to *be* life.

The chemical process ... displays the dialectic by which all the particular properties of bodies are drawn into transitoriness. ... It is therefore solely the being-for-self of infinite form which endures, the pure incorporeal individuality which is for itself, and for which material subsistence is simply a variable. The chemical process is the highest expression of inorganic being ... ; [it] constitutes the transition to the higher sphere of the organism. ...⁶⁸

So in the chemical process, nature is just about to reach the categorial stage of life, which manifests itself as subjectivity, that is, as an inner being that dissociates its inte-

rior from its exterior. Since, however, the world of living organisms is beyond the scope of the present chapter,⁶⁹ my overview of Hegel's *Mechanics and Physics* concludes at this point.

4. Problems Inherent in the Sciences According to Hegel

Even though – as we have seen – Hegel holds, on the one hand, that any philosophy of nature should be in accordance with the results of the respective contemporary sciences, he holds, on the other hand, that there are severe problems inherent in the general methods of the sciences. To be sure, these problems largely do not appear *within* scientific work itself; they occur rather when scientific results and methods are taken – without the critical guidance of philosophy – as a basis for constructing a *world-view*. The following features of science appear especially problematic to Hegel in this respect:

- The annihilation of *qualitative differences* in the course of scientific progress (Section 4.a below)
- The *atomistic* consideration of nature (Section 4.b)⁷⁰
- The search for *dynamical laws* of nature and their being preferred to phenomenological laws (Section 4.c).⁷¹

4.a. *The Sciences' Annihilation of Qualitative Differences*

Like Kant, Hegel is fully aware that scientific work *necessarily* involves abstraction and mathematization. He is far from considering this to be per se a problematic feature of the sciences. He concedes that scientific descriptions of natural phenomena are fundamentally mathematical and abstract. Abstractness is, of course, also a feature of philosophical views of nature:

The more thought predominates in ordinary perceptiveness, so much the more does the naturalness, individuality, and immediacy of things vanish away. As thoughts invade the limitless multiformity of nature, its richness is impoverished, its springtimes die, and there is a fading in the play of its colours. That which in nature was noisy with life, falls silent in the quietude of thought; its warm abundance, which shaped life itself into a thousand intriguing wonders, withers into arid forms and shapeless generalities, which resemble a dull northern fog.⁷²

Gerd Buchdahl called these phrases some of Hegel's truly memorable formulations.⁷³ They certainly are; and they make clear that Hegel is *not* opposing the abstractness of any (scientific or philosophical) view of nature. What he is opposing is rather the *annihilation of qualitative differences* within the realm of nature as a result of scientific work, or rather as a result of a specific style of scientific work. Hegel's contention is that a proper understanding of the essence of nature is impossible if the human intellect puts "everything on the same level," that is, if it does not take into account the categorial determinateness of the individual stages of nature.⁷⁴ Broadly speaking, new levels of determinateness emerge, according to Hegel, not merely through aggregation or the

summation of parts, but through new *modes of relation* that add new qualities to the parts. In the addition to §286 of the *Encyclopaedia*, Hegel's criticism of reductionist approaches in the sciences is expressed in the following way:

The attempt is made to put everything on the same level. *Everything* can of course be treated from a chemical point of view, but everything can also be treated from a mechanical point of view. ... When bodies are treated at one stage, this does not exhaust the nature of other bodies however, as for example when vegetable or animal bodies are treated chemically.⁷⁵

It cannot be denied that there is a deep truth in these claims. Hegel defends the old view of nature as a system of qualitatively distinct stages, as it was understood to be in the concept of the *scala naturae* or the "great chain of being."⁷⁶ The idea of a *scala naturae* ascribes – as noted by Arthur Lovejoy – three basic features to the universe: *plenitude*, *continuity*, and *gradation*. The principle of *plenitude* states that the universe exhibits the greatest possible diversity of kinds of existence. According to the principle of *continuity*, the universe is composed of an infinite series of forms, each of which shares with its neighbor at least one attribute. According to the principle of *gradation*, finally, this series ranges in hierarchical order from the barest type of existence to the most perfect conceivable entity (i.e., God).⁷⁷ While Hegel evinces some skepticism toward the principle of continuity,⁷⁸ he does defend the view that nature has a hierarchical order and represents a *system of forms*.⁷⁹ At the same time, he rightly points out that 'modern' science tends to overlook or to doubt the existence of qualitative differences in nature.⁸⁰ Especially when new tools, proving powerful in the mathematical treatment of natural phenomena, are developed (such as Newton's concept of force or – after Hegel's death – the concept of energy conservation), it regularly happens that nature is seen almost exclusively in the light of these. Formulations such as the following then typically prevail: "The whole realm of nature is governed by forces, the differences consist *only* in the respective kinds of acting forces," or "Energy conservation governs *all* natural processes, both in the inorganic and in the organic world," or "The struggle for existence creates *all* forms in nature." In his *Philosophy of Nature*, Hegel shows quite a pronounced hostility toward this *type* of view (some of them, of course, had not been explicitly developed during his lifetime), each of which tries to reduce the full range of the *scala naturae* to one or to very few of its stages.

This *antireductionism* is one of the chief strengths of Hegel's philosophy of nature⁸¹ – and moreover of his system in general. One might argue, of course, that science would be impossible without some sort of reductionism.⁸² However, given that the specific stages or principles *to which* – more or less successfully – the complexity of nature is reduced vary significantly in the course of history,⁸³ it is necessary to point out the limited validity of any particular version of reductionism.⁸⁴ This is precisely what Hegel does, even though his attacks are, unfortunately, in several instances focused too much on Newton's particular model of reducing natural phenomena to forces.

Furthermore, it is worth pointing out – even though it cannot be demonstrated here in detail – that Hegel's criticism of reductionist world-views paves the way for a non-reductionist philosophy of mind. Only by conceiving a hierarchical system of categories, within which it is illegitimate at *any* point to explain a more complex level *wholly* in terms of basic levels (i.e., to call them "nothing but" arrangements or combinations of

the basic levels), can Hegel elaborate a philosophical “anthropology” and “psychology” in a nonreductive way.⁸⁵ By contrast, a philosophy of mind that tries to oppose the reduction of mind to mere properties of matter *without* a general concept of qualitatively distinct ontological levels deprives itself of strong points that Hegel has to make, one of which is still to follow below.

4.b. *The Atomistic View of Nature, Or, Why Hegel Would Have Preferred Quarks to Atoms*

Hegel’s criticism of the atomistic view of nature is motivated by his antireductionist orientation. This is of course consistent since *philosophical atomism* is a *prototype of reductionism*. According to Hegel, atomism fails to grasp the essence of *natural unities* such as planets, solar systems, plants, and animals. All these natural unities are more than mere sums of their parts; conversely, their parts exist only as “sublated” (*aufgehoben*) and as transformed moments of qualitatively new entities.⁸⁶ In contrast, on the basis of atomism, “all union becomes merely mechanical; ... the united elements nevertheless remain remote from one another.”⁸⁷

As for the atoms and molecules conceived by eighteenth- and nineteenth-century physics in particular, we find the following statement in the Remark to §298 of Hegel’s *Encyclopaedia*:

Wherever the question of material *parts* arises, one should not think of them as atoms or molecules, i.e. as separated and self-subsistent, but as merely quantitatively ... distinguished, so that their *continuity* is essentially inseparable from their *distinctness*.⁸⁸

It is hence *not the physical atom in itself* that Hegel considers as a problematic concept, but rather its being conceived as “separated and self-subsistent.” The background is the following: Hegel tends to argue that *all entities* (everything that can actually be thought, i.e., that can be thought in a *coherent* manner) exist exclusively by virtue of their relatedness to other entities. Hence he ultimately denies the existence of entities that are *per se* – independently of their relations to others – ultimate building blocks of reality.

This attitude has its merits both within the theory of state – where it makes intersubjectivity a more suitable starting point than mere individuality – and the philosophy of nature. However, in the latter domain the way in which Hegel elaborates it is not always convincing.

For example, when treating the meteorological process, Hegel states: “Rain comes, so to speak, out of dry air.”⁸⁹ He opposes the view according to which water droplets or water vapor are contained in the air as a necessary precondition for rain. On the contrary, he holds that rain is an example of a real transformation of (dry) air into water within the process of the elements. In the same context, he even goes so far as to dispute the extraterrestrial origin of meteorites, which he considers as solid precipitates of the atmosphere. Processes such as precipitation of rain out of entirely dry air would seem to us miraculous today – and even more so the formation of meteorites in the Earth’s atmosphere. However, these issues were still matters of debate among scientists in the first quarter of the nineteenth century.⁹⁰ Hegel’s views on these subjects show that he did *not* have anything in mind like a ‘principle of mass conservation’ in closed systems.

This is precisely because of his skepticism toward regarding material atoms as self-subsistent, imperishable building blocks of nature. The Hegelian idea of nature leaves more room for a ‘*creatio ex nihilo*’ (or rather a ‘*creatio ex conceptu*’) than for any sentence such as: ‘The number of atoms in a closed volume remains constant over time.’

Are we forced to say, in the light of today’s scientific views, that Hegel’s critical attitude toward atomism has been altogether falsified? Certainly not. Rather, the crux is the *specific level* at which Hegel thinks that atoms represent mere moments or easily transformable entities. Within the meteorological process, atoms – and even water molecules – largely act as indissoluble compounds; hence on *this level*, Hegel was too optimistic about their being ‘mere moments.’ In stellar interiors, by contrast, atoms are in fact mere ‘moments’ of nuclear processes that transform them into one another and that even transform mass into energy. Indeed, due to the transformation of mass into energy, we cannot say that the number of atoms remains constant over time in a (hypothetically) closed volume element inside a star. This is, of course, only a particular case, insufficient as an example in favor of Hegel’s theory. However, the smallest units of present-day elementary physics, *quarks*, provide an additional argument. Quarks are conceived as elementary particles that do *not occur at all as self-subsistent natural unities*. Quarks build up matter only by occurring in different combinations – or, as we might put it in a Hegelian way, by virtue of different modes of relatedness.

Should today’s standard model of elementary particles stand the test of time, this would interestingly imply a late confirmation of the Hegelian axiom ‘relatedness first,’ since this standard model involves a theory of matter in which at least some of the smallest basic units, the quarks, have no self-subsistence in nature and can be transformed into one another (by means of the so-called weak interaction).

4.c. *Phenomenological Versus Dynamical Laws of Nature – Or, Why Hegel Prefers Kepler to Newton*

One of the most fundamental points of disagreement between Hegel and modern scientific approaches to nature concerns the role of *forces* in the description and (especially) explanation of natural phenomena. This is equivalent to saying that *dynamical laws* of nature – natural laws involving force terms – are something against which Hegel has a point to make, even though they turned out to be a powerful tool in science.

It is generally known that Kepler – whom Hegel admires and praises very much for finding the three laws of planetary motion – also used the term ‘force’ repeatedly in his oeuvre, and speculated about a magnetic origin of the forces keeping the planets in their orbits around the Sun. However, no force terms enter explicitly into the three Keplerian laws. Furthermore, Kepler’s laws are not meant to be *universal* natural laws, but rather *laws of particular phenomena* – though, as we know today, very widespread ones, namely planetary motions. Kepler’s laws have not yet led to a unified description of terrestrial and celestial motions. By contrast, Newton’s law of gravitation is both a law explicitly containing a *force term* and a *universal law* of nature. It encompasses, for example, Kepler’s third law and Galileo’s law of free fall. And – what is more – it was formulated by Newton in the course of a *quest for basic forces* on which *all* natural phenomena were suspected to depend. “The whole burden of philosophy,” says Newton in the Preface to the first edition of his *Principia*,

seems to consist in this – from the phenomena of motions to investigate the forces of nature, and then from these forces to demonstrate the other phenomena. ... I am induced by many reasons to suspect that they [i.e., the phenomena of nature] may all depend upon certain forces by which the particles of bodies, by some causes hitherto unknown, are either mutually impelled towards each other, and cohere in regular figures, or are repelled and recede from one another. These forces being unknown, philosophers have hitherto attempted the search of Nature in vain; but I hope the principles here laid down will afford some light either to this or some truer method of philosophy.⁹¹

Hence, it is quite appropriate to call Kepler's laws "phenomenological laws," while Newton's law of universal gravitation may be termed a "dynamical [=force-based] law." Other dynamical laws include Coulomb's law of electrostatics and Maxwell's equations, while an additional example of a phenomenological law is Snell's law of refraction. Hegel indeed uses this terminology in his *Lectures on the History of Philosophy* when writing that Newton "set the laws of forces in the place of the [Keplerian] laws of phenomena."⁹² Now while scientists are generally used to having higher esteem for dynamical laws than for phenomenological ones (mainly due to the higher degree of universality characterizing the former), Hegel has the opposite preference, as has already been observed, for example, by Buchdahl⁹³ and Falkenburg.⁹⁴ According to Hegel, the main problem inherent in the description of nature by means of dynamical laws is the *explanatory power* that is claimed for them. On the one hand, Newton assigns a very strong 'physical' meaning to forces by saying – as cited above – that they are the entities on which *all* natural phenomena (probably) depend. On the other hand, at the end of his *Principia*, in the *Scholium generale*, Newton famously declares that he does not have any real explanation for the properties of gravity and does not wish to frame any hypotheses.⁹⁵ Hegel finds it very dissatisfying that every physical explanation should be based on forces that in turn are declared to be essentially inexplicable. His suggestion on this point, as put forward in the lectures on the philosophy of nature from 1825/1826, reads thus: "If nothing ought to be determined physically [as Newton pretends], then the term 'force' should be totally omitted."⁹⁶ Interestingly, this suggestion has also been made by physicists who had almost certainly not read Hegel. Heinrich Hertz, in the introduction to his *Principles of Mechanics*, calls (Newtonian) forces "needless auxiliary wheels" and stresses – much in same way as Hegel – that forces are usually *not* subjects of experience.⁹⁷ The development of nineteenth- and twentieth-century physics in fact led partly to the replacement of the concept of force by the concept of energy and partly to the 'geometrization' of forces that we encounter in the General Theory of Relativity. None of these developments were aimed at or influenced by Hegel, but they were motivated by criticisms of the concept of force that have remarkable similarities with Hegel's; this is one more motivation for continuing to take the latter seriously today.⁹⁸

5. Conclusions

Hegel's *Philosophy of Nature* has been criticized throughout the past 200 years for its alleged nonconformity with essential results of the sciences. Many authors considered

this part of his encyclopedic system to be the weakest one, and partly for reasons that sounded convincing to the impartial reader.

Starting around 1970, the attempt has been made to re-examine the relation between Hegel and the sciences in a thorough way, questioning and avoiding earlier prejudices. Nowadays – even though many statements on *individual* topics contained in the *Philosophy of Nature* may seem to contrast even more strongly with current scientific views than at the time they were written – it can be seen more clearly that Hegel did have serious points to make against specific aspects of scientific methods (or of *the* scientific method). These points include Hegel's criticism of the annihilation of qualitative differences in nature, his criticism of various kinds of science-based reductionism, and his idea that replacing phenomenological laws (having explicitly restricted domains of validity) with universal dynamical laws of nature does not in every respect constitute progress. Some of these problems have also been highlighted by scientists who lived several decades after Hegel and who were not directly influenced by him – a fact that may be interpreted as “independent confirmation” of Hegelian views on the sciences.

Generally, however, Hegel aimed at a philosophy of nature in *accordance* with the results of science. Its task would be to answer questions such as “What is nature?” “What is space and time?” “What is life?” or, more specifically, “How can the realms of nature be structured based on a predefined system of categories (developed in the *Science of Logic*) so as to proceed, in a nonreductive way, from lower to higher levels of complexity?” One may possibly object that these questions cannot be answered at all. But hardly anybody would dare to say that they have been or will soon be answered by the sciences themselves.

Of course, we do not have to consider the Hegelian answers to the above questions to be authoritative, but ignoring them means – to say the least – the loss of valuable tools for finding adequate answers.

Notes

- 1 *Hegel's Philosophy of Nature*, ed. and trans. with an Introduction and Explanatory Notes by Michael J. Petry. (London and New York: Allen and Unwin, 1970), vol. 1, p. 191 (= *Encyclopaedia of the Philosophical Sciences in Outline*, §244, addition).
- 2 Note that these are Hegel's words against Schelling and his disciples (*ibid.*).
- 3 Cf. Karl Rosenkranz, *Hegel's Naturphilosophie und die Bearbeitung derselben durch den italienischen Philosophen Augusto Vera* (Berlin: Nicolaische Verlagsbuchhandlung, 1868; reprinted Hildesheim: Georg Olms, 1979), 13: “It may be said that the prejudice against Hegel's philosophy in Germany has nowhere reached the same resoluteness as it has with respect to his philosophy of nature” (my translation).
- 4 H.-J. Treder, “Zum Einfluß von Schellings Naturphilosophie auf die Entwicklung der Physik,” in *Natur und geschichtlicher Prozeß*, ed. H. J. Sandkühler (Frankfurt am Main: Suhrkamp, 1984), 327.
- 5 James Hutchison Stirling, *Lectures on the Philosophy of Law, Together with Whewell and Hegel, and Hegel and Mr. W. R. Smith: A Vindication in a Physico-mathematical Regard* (London: Longmans, Green, 1873), 70.
- 6 Cf. W. Whewell, “On Hegel's Criticism of Newton's Principia,” *Transactions of the Cambridge Philosophical Society* 8, Part V (1849): 696–706.

- 7 Michael J. Petry, in the Introduction to his edition of *Hegel's Philosophy of Nature*, states: "There can be very few works of this importance that have remained so completely unappreciated for so long." (loc. cit., vol. 1, 114.)
- 8 Cf. Plato, *Timaeus*, 34b–36d.
- 9 Cf. Hegel, *Dissertatio Philosophica de Orbitis Planetarum*, ed. and trans. by Wolfgang Neuser (Weinheim: VCH Verlag, 1986), 138: "Quae series si verior naturae ordo sit, quam illa arithmetica progressio, inter quartum et quintum locum magnum esse spatium, neque ibi planetam desiderari apparet." ("If this series [i.e., the one from Plato's *Timaeus*] really does give the true order of nature as an arithmetic series, then there is a great space between the fourth and fifth places where no planet appears to be missing." Translation: David Healan.)
- 10 E. Craig and M. Hoskin, "Hegel and the Seven Planets," *Journal for the History of Astronomy* 23 (1992): 208–209.
- 11 Cf. Matthias Jakob Schleiden, *Schelling's und Hegel's Verhältnis zur Naturwissenschaft* (Leipzig: Engelmann, 1844), 41: "In 1801, Hegel had dialectically annihilated the asteroids. In 1801, Ceres was discovered, in 1802, Pallas was discovered" (my translation).
- 12 John W. Burbidge, *Real Process. How Logic and Chemistry Combine in Hegel's Philosophy of Nature*. (Toronto: University of Toronto Press, 1996), 15.
- 13 Cf. *Hegel's Philosophy of Nature*, loc. cit., vol. 1, p. 197: "It is not only that philosophy must accord with the experience nature gives rise to; in its *formation* and in its *development*, philosophic science presupposes and is conditioned by empirical physics" (*Encyclopaedia of the Philosophical Sciences*, §246, Addition).
- 14 John W. Burbidge, loc. cit., 21.
- 15 *Hegel's Philosophy of Nature*, ed. Petry, loc. cit., vol. 2, 17. I have taken the liberty of replacing "Notional determination" with "Conceptual determination." The original term is "Begriffsbestimmung."
- 16 *Ibid.*, 12. Again, "Notional determination" has been replaced with "Conceptual determination."
- 17 *Ibid.*
- 18 *Ibid.*, 11. In Petry's translation, we find the term "variety" for the German word "Verschiedenheit," but "diversity" is probably a more adequate translation.
- 19 *Hegel's Philosophy of Nature*, ed. Petry, loc. cit., vol. 1, p. 230 (*Encyclopaedia of the Philosophical Sciences*, §258).
- 20 For example, a dialectical step contains normally three moments in the sphere of Logic and in the sphere of spirit, whereas it can contain four – in some cases even five – moments in the nature, as stated in the Addition to §248: "In nature taken as otherness, the square or tetrad also belongs to the whole form of necessity, as in the four elements, the four colours etc.; the pentad may also be found, in the five fingers and the five senses for example; but in spirit the fundamental form of necessity is the triad. The second term is difference, and appears in nature as a duality, for in nature the other must exist for itself as an otherness. Consequently, the subjective unity of universality and particularity is the fourth term, which has a further existence as against the other three. In themselves the monad and the dyad constitute the entire particularity, and the totality of the Notion itself can therefore proceed to the pentad" (*Hegel's Philosophy of Nature*, ed. Petry, loc. cit., vol. 1, p. 211).
- 21 *Hegel's Philosophy of Nature*, ed. Petry, loc. cit., vol. 2, p. 205: "Nature has yielded itself [i.e., at the end of the *Science of Logic*] as the Idea in the form of *otherness*. Since the *Idea* is therefore the negative of itself, or *external to itself*, nature is not merely external relative to this Idea (and to the subjective existence of the same, spirit), but is embodied as nature in the determination of *externality*." (An alternative way of translating the last phrase is: "Externality constitutes the determination in which nature as nature exists.") On the relation between "Idea in the form of otherness" and "externality," see William Maker,

- “The Very Idea of the Idea of Nature, or Why Hegel Is Not an Idealist,” in: *Hegel and the Philosophy of Nature*, ed. Stephen Houlgate (Albany: State University of New York Press, 1998), 12.
- 22 Carl Siegel, *Geschichte der deutschen Naturphilosophie* (Leipzig: Akademische Verlagsgesellschaft, 1913), 220.
- 23 Hegel – according to the edition prepared by Michelet – says in the concluding passage of the Addition to §270: “Philosophy has to proceed on the basis of the Notion, and even if it demonstrates very little, one has to be satisfied. It is an error [!] on the part of the philosophy of nature to attempt to face up to all phenomena. ... philosophy need not be disturbed if the explanation of each and every phenomenon has not yet been completed” (*Hegel’s Philosophy of Nature*, ed. Petry, loc. cit., vol. 1, p. 281).
- 24 As for the term *ontologia specialis* in relation to Hegel’s system, cf. Dieter Wandschneider, who correlates the *Science of Logic* with the traditional *ontologia generalis* and both *Philosophy of Nature* and *Philosophy of Spirit* with the traditional *ontologia specialis* (Dieter Wandschneider, “Die Stellung der Natur im Gesamtentwurf der Hegelschen Philosophie,” in *Hegel und die Naturwissenschaften*, ed. Michael J. Petry (Stuttgart – Bad Cannstatt: Frommann-Holzboog, 1987), 33–64, esp. 38). It is particularly within *ontologia specialis* that a priori deductions become problematic. Hegel himself uses the term “Realphilosophie” as equivalent of *ontologia specialis*.
- 25 Cf. Hegel’s *Philosophy of Right*, trans. T. M. Knox (Oxford: Oxford University Press, 1942), 11: “Plato might have omitted his recommendation to nurses to keep on the move with infants and to rock them continually in their arms. And Fichte too need not have carried what has been called the ‘construction’ of his passport regulations to such a pitch of perfection as to require subjects not merely to sign their passports but to have their likenesses painted on them. Along such tracks all trace of philosophy is lost, and such super-erudition it can the more readily disclaim since its attitude to this infinite multitude of topics should of course be most liberal.”
- 26 Cf. *Hegel’s Philosophy of Nature*, ed. Petry, loc. cit., vol. 1, 215 (§250): “The impotence of nature is to be attributed to its only being able to maintain the determinations of the Notion in an abstract manner. ...”
- 27 Ibid. (§250 remark). Again, Petry’s translation has been modified here: “Notion” has been replaced with “Concept.”
- 28 Stephen Houlgate, “Introduction” to *Hegel and the Philosophy of Nature*, ed. by Stephen Houlgate (Albany: State University of New York Press, 1998), xiii–xiv: “Some argue that the structure or skeleton of the *Philosophy of Nature* is developed purely conceptually, but that the flesh, as it were, is derived from empirical observation and scientific experimentation and analysis. On this view, Hegel is led to the very idea of nature by the *Science of Logic*, develops the conceptual structure of nature a priori from the initial determination of nature as abstract externality, and then ‘maps’ natural phenomena as described by science on to the various conceptual determinations that arise. ... Others argue, however, that scientific discoveries themselves condition, and perhaps even determine, the development of Hegel’s conceptual account of nature.” Cf. also Houlgate’s extensive discussion of this point in his *An Introduction to Hegel* (Oxford: Blackwell, 2005), 115–121.
- 29 Cf. Also William Maker, loc. cit., 19–20: “Hegel articulates a philosophy of nature which ... provides an a priori account of nature, not as it is given in all its specificity (as that must fall beyond systematic thought), but in terms of delineating and accounting for the general features of givenness as such.”
- 30 Ibid.
- 31 Organics – the third part of the *Philosophy of Nature* – will not be covered here since it is the topic of Cinzia Ferrini’s contribution to this volume.

- 32 *Hegel's Philosophy of Subjective Spirit*, ed. and trans. Michael J. Petry, vol. 1: Introductions (Reidel: Dordrecht/Boston, 1978), 37.
- 33 Cf. Hegel's *Philosophy of Nature*, ed. Petry, loc. cit., vol. 1, p. 229 (Addition to §257): "Space and time are generally taken to be poles apart: space is there, and then we *also* have time. Philosophy fights against this mere 'also'" ("dieses 'Auch' bekämpft die Philosophie"; translation emended). Note that this may even be considered as a definition of dialectic philosophy, according to which thought "fights" against the ordinary representation insofar as the latter considers concepts and things as originally independent from or external one to another, relations between them being mere epiphenomena. Philosophical thought, at least after Hegel, has to invert this order.
- 34 Cf. Hegel, *Vorlesung über Naturphilosophie Berlin 1821/22* [Manuscript Uexküll], ed. Gilles Marmasse and Thomas Posch (Frankfurt am Main: Peter Lang, 2002), 42: "Beide [=Materie und Bewegung] sind ein und dasselbe; die Verschiedenheit beider besteht nur darin, daß die Materie eben die Wahrheit des Raums und der Zeit ist, und zwar gesetzt auf einfache, selbst unmittelbar ruhende Weise, in der Weise des Raums. Dies Resultat nun gesetzt in der Form des Prozesses oder der Zeit, ist die Bewegung." ("Matter and motion are the same; their difference is just the following: matter is the truth of space and time, posited in a simple, immediate, quiescent way – in a spatial way. This result, posited in a processual form, or in a temporal form, is motion.")
- 35 Cf. *Hegel's Philosophy of Nature*, ed. Petry, loc. cit., vol. 1, p. 248 (Addition to §265; note that Hegel speaks of "force" here where he should actually speak of "impact").
- 36 In §214 of the 1817 edition of his *Encyclopaedia*, Hegel thus says: "This motion [i.e., motion as considered in finite mechanics] transforms itself for itself into rest."
- 37 John Burbidge, *Real Process. How Logic and Chemistry Combine in Hegel's Philosophy of Nature*, loc. cit., 111.
- 38 *Hegel's Philosophy of Nature*, loc. cit., vol. 1, p. 282 (Addition to §271; translation emended).
- 39 *Ibid.*, vol. 2, p. 9 (Addition to §272). On the meaning of "individuality" in Hegel's *Philosophy of Nature*, see the illuminative comment by John Burbidge in *Real Process*, loc. cit., 109–111.
- 40 To cite, once again, John Burbidge: "the middle section on physics stands between nature considered abstractly or universally and nature considered as integrated, singular organisms. The characteristics described are ways of differentiating among natural entities. Physics is nature particularized" (Burbidge, *Real Process*, 110).
- 41 *Hegel's Philosophy of Nature*, loc. cit., vol. 2, p. 17 (§276).
- 42 How does pure self-identity relate to individuality? The human self, or the I, may be taken as a conceptual model illustrating this. The I is in the sphere of spirit what light is in the sphere of nature: reflective self-identity, which, in its reflection, marks the beginning of individuality. Cf. *ibid.*, 13: "This [i.e., the concept of light] is pure intro-reflection which, in the higher form of spirit, is the ego. The ego is infinite space, the infinite equality of self-consciousness with itself, the abstract and empty certainty of myself, and of my pure self-identity. The ego is merely the identity of my own attitude as subject, to myself as object. Light corresponds to this identity of self-consciousness, and is the exact image of it."
- 43 Since we know today that many – probably most – stars have planets around them, we may even more expressly say that the difference between stars and suns is merely one of the respect in which we regard it (i.e., as self-sustaining natural source of light or center of a planetary system). Note, however, that Hegel already envisaged the same kind of difference.
- 44 *Hegel's Philosophy of Nature*, loc. cit., vol. 1, p. 211 (Addition to §248).
- 45 Cf. *Hegel's Philosophy of Nature*, loc. cit., vol. 2, p. 31 (§280 Remark): "We now come to stand upon the Earth ... , which is not only our physical, but also spiritual home."

- 46 G.W.F. Hegel, *Jenaer Systementwürfe II: Logik, Metaphysik, Naturphilosophie*, ed. Rolf-Peter Horstmann. (Hamburg: Felix Meiner, 1982), VI.
- 47 Hegel's *Philosophy of Nature*, loc. cit., vol. 2, p. 34 (§281 Remark).
- 48 Ibid.
- 49 Cf. *ibid.*, 33, where Hegel speaks of the chemical elements as “volatilized into chemical abstraction” (§281 Remark).
- 50 *Ibid.*, 35 (Addition to §281).
- 51 G.W.F. Hegel, *Naturphilosophie. Die Vorlesung von 1819/20* [Manuscript Bernhardy], ed. Manfred Gies (Napoli: Bibliopolis, 1982), 48.
- 52 *Hegel's Philosophy of Nature*, loc. cit., vol. 2, p. 38 (§283).
- 53 Cf. G.W.F. Hegel, *Naturphilosophie. Die Vorlesung von 1819/20* [Manuscript Bernhardy], loc. cit., 49: “als formlos schließt es alle Form in sich.” See also *Vorlesung über Naturphilosophie Berlin 1821/22* [Manuscript Uexküll], loc. cit., 101: “gleichgültig gegen die Gestalt, ist das Wasser ... die Möglichkeit verschiedener Gestaltungen.”
- 54 Cf. G.W.F. Hegel, *Naturphilosophie. Die Vorlesung von 1819/20* [Manuscript Bernhardy], loc. cit., 49: “Begriff der Individualität überhaupt.”
- 55 *Jenaer Systementwürfe II. Logik, Metaphysik, Naturphilosophie*, ed. Rolf-Peter Horstmann (Hamburg: Felix Meiner, 1982), 292: “Die Erde als das Redukt der Elemente ist passiv sich auf sich selbst beziehend, und damit selbst Bestimmtheit.”
- 56 In fact, many natural plasmas (e.g., the solar wind) are hot; the plasma state of matter is also a “dissolved” or “dissolving” one insofar as electrons are detached from atomic nuclei in plasma.
- 57 *Ibid.*, 82 (§303).
- 58 The second law of thermodynamics has been formulated, in different versions, by Lord Kelvin (Sir William Thomson, 1824–1907), Rudolf Clausius (1822–1888) and others. I'm here not referring to any particular version of this law, but to its consequence that in closed natural systems, entropy will always increase with time, which in many cases leads to an increase of disorder with time, which in turn corresponds to transitions from form to “formlessness.”
- 59 *Ibid.*, 85 (§304, Remark). Hegel refers to the experiments with the heating of bodies by friction, carried out by Benjamin Thompson (1753–1814) Count Rumford.
- 60 Cf. Thomas Posch, “Die Rezeption der Hegelschen Lehre von der Wärme durch C. L. Michelet und K. R. Popper,” in *Wiener Jahrbuch für Philosophie* 34 (2002): 143–158. See also Thomas Posch, *Die “Mechanik der Wärme,” in Hegels Jenaer Systementwurf von 1805/06: Ein Kommentar vor dem Hintergrund der Entwicklung der Wärmelehre von 1620 bis 1840* (Aachen: Shaker Verlag, 2005).
- 61 *Hegel's Philosophy of Nature*, loc. cit., vol. 2, p. 96 (§310).
- 62 *Ibid.*, 96 (Addition to §310).
- 63 In fact, Hegel calls the crystal the “quiescent end” (*daseiender Zweck* [télös]); *ibid.*, 114 (Addition to §315).
- 64 Cf. *ibid.*, 99 (§312).
- 65 As Hegel puts it: “The two poles [that we had in magnetism] as existing separately from each other, each pole carried by an individual body, this is electricity” (G.W.F. Hegel, *Vorlesungen über Naturphilosophie Berlin 1825/26* [Manuscript Dove], ed. Karol Bal et al. (Hamburg: Felix Meiner, 2007), 154 (my translation)).
- 66 Cf. *ibid.*: “This is the electrical movement: to posit identical the different and to differentiate the identical” (my translation).
- 67 Cf. Addition to §200 of Hegel's *Encyclopaedia* (section on “Chemism”). In the *Science of Logic*, Hegel points out the applicability of the category of chemism also to love and friendship. This merely illustrates that chemism, according to Hegel, is indeed a very general

- form of object relation; it is *not* meant as a reductionist consideration of love and friendship.
- 68 *Hegel's Philosophy of Nature*, loc. cit., vol. 2, p. 222 (Addition to §336).
- 69 As for the section "Organics," see Chapter 9 in this volume.
- 70 Haering, in an essay from 1931, already pointed to Hegel's opposition to the former two tendencies of modern science. Cf. Thomas Haering, "Hegel und die moderne Naturwissenschaft ["Hegel and Modern Science"]": Bemerkungen zu Hegels Naturphilosophie," in *Philosophische Hefte* 3, no. 1/2 (1931): 71–82. While Haering, however, fully affirmed Hegel's positions in this regard, I shall try to take up a more differentiated stance.
- 71 The third point has been highlighted, *inter alia*, by Buchdahl and Falkenburg. Cf. Gerd Buchdahl, "Conceptual Analysis and Scientific Theory in Hegel's Philosophy of Nature," in *Hegel and the Sciences*, ed. Robert S. Cohen and Marx W. Wartofsky (Dordrecht: Reidel, 1984), 13–36; Brigitte Falkenburg, "How to Save the Phenomena: Meaning and Reference in Hegel's Philosophy of Nature," in *Hegel and the Philosophy of Nature*, ed. Stephen Houlgate (Albany: State University of New York Press, 1998), 97–135.
- 72 *Hegel's Philosophy of Nature*, vol. 1, p. 198 (§246 Remark).
- 73 Buchdahl, loc. cit., p. 19. Buchdahl refers to Miller's translation of the Remark to §246, in which the essential phrase reads: "The rustle of Nature's life is silenced in the stillness of thought."
- 74 As for the term "stages," cf. §249 of the *Encyclopaedia*: "Nature is to be regarded as a *system of stages*. ..."
- 75 *Hegel's Philosophy of Nature*, loc. cit., vol. 2, p. 43 (Addition to §286). Cf. *ibid.*, vol. 1, p. 201: "The current philosophy is called the philosophy of identity. It might be much more appropriate to apply this name to this kind of physics, which simply dispenses with determinateness. It is a fault in physics that it should involve so much identity, for identity is the basic category of understanding" (Addition to §246).
- 76 For the history of the concept of *The Great Chain of Being*, cf. Arthur Lovejoy's study with this title (Cambridge, Mass.: Harvard University Press, 1936). However, Hegel does not play a particular role in Lovejoy's version of the story of this concept.
- 77 Cf. *The New Encyclopaedia Britannica*, 15th edition (Chicago: University of Chicago Press, 2005), vol. 5, p. 442.
- 78 Cf. Michael J. Petry, *Hegel's Philosophy of Nature*, vol. 1, pp. 214–215: "The old saying, or law as it is called, 'non datur saltus in natura' is by no means adequate to the diremption of the Notion. The continuity of the Notion with itself is of an entirely different nature" (Addition to §249).
- 79 See also Michael J. Petry, *Hegel's Philosophy of Nature*, vol. 1, Introduction, pp. 21–40, Section "Levels, Hierarchies and Spheres."
- 80 *Ibid.*, 30.
- 81 Cf. Thomas Posch, "Hegel's Anti-reductionism: Remarks on What Is Living of His Philosophy of Nature," *Angelaki: Journal of the Theoretical Humanities* 10, no. 1 (April 2005): 61–76.
- 82 As for a contemporary definition of antireductionism, cf., e.g., John Polkinghorne: "[Physics] pulls things apart into smaller and smaller pieces. We have learned all sorts of worthwhile and interesting things this way. The question is whether or not it is the only way to learn what things are *really* like. In the end, are we just immensely complicated collections of quarks, gluons, and electrons? People who answer 'Yes' to this last question are called reductionists. In their view, the whole reduces simply to a collection of the parts. They are sometimes also called 'nothing butters', for they believe we are 'nothing but' collections of elementary particles. Those ... who do not share this view are called antireductionists." See John Polkinghorne, *Quarks, Chaos and Christianity* (New York: Crossroads Publications, 1996), 51.

- 83 For example, Aristotle notoriously considers the living organism and its entelechy a sort of paradigm for the description of natural phenomena; Newton uses mechanical forces as a paradigm of his physics; several physicists of the nineteenth century assigned a similar role to the concept of energy (as mentioned above).
- 84 Cf. Richard Kroner, *Von Kant bis Hegel*, vol. 2, loc. cit., p. 249: “Der Philosophie fällt daher das Wächteramt zu, kraft dessen sie jeden Uebergriff einer empirischen in eine andere Disziplin, bzw. in die Philosophie selbst, zu verhüten und die *Grenzen der Wissenschaften* mit kritischer Strenge zu schützen hat.” (“It is hence up to philosophy to prevent the encroachment of any one empirical discipline into another or into philosophy itself; it is up to her to guard the *limits of individual sciences* with critical rigor.”)
- 85 On Hegel’s Philosophy of Mind, cf. Chapter 10 in this volume.
- 86 It is in the same context that Hegel holds that the *evolution of species* is not properly understood (or rather, that evolution is not a useful concept at all) if understood merely as the sum of a huge number of tiny steps.
- 87 G.W.F. Hegel, *Lectures on the History of Philosophy 1825–6*, Vol. 2: Greek Philosophy, ed. Robert F. Brown (Oxford: Oxford University Press, 2006), 92. Hegel goes on to say there, treating Leucippus and Democritus: “The bond between [the atoms] is only external; it is a combination, for there is no actual union or unity.”
- 88 *Hegel’s Philosophy of Nature*, loc. cit., vol. 2, pp. 66–67, emphasis added.
- 89 *Ibid.*, vol. 2, p. 46. As for the context in which the meteorological process is treated in the Philosophy of Nature, see above, Section 3b.
- 90 For example, the Swiss geologist and meteorologist Jean André Deluc (1727–1817) still denied the extraterrestrial origin of the meteorites; so did the German physicist Johann Tobias Mayer (1752–1830). Cf. Petry’s more extensive notes in this subject in *Hegel’s Philosophy of Nature*, loc. cit., vol. 2, p. 278.
- 91 *Sir Isaac Newton’s Mathematical Principles of Natural Philosophy*, ed. F. Cajori (Cambridge: Cambridge University Press, 1934), xvii–xviii.
- 92 G.W.F. Hegel, *Lectures on the History of Philosophy*, trans. E. S. Haldane and Frances H. Simson (London: Kegan Paul, Trench, Trübner & Co., 1895), vol. 3, p. 323, emphasis added.
- 93 Cf. Gerd Buchdahl, “Conceptual Analysis and Scientific Theory in Hegel’s Philosophy of Nature,” loc. cit., 20, 25. (Buchdahl explicitly speaks of Hegel’s “preference for the use of phenomenological theory-types.”)
- 94 Cf. Brigitte Falkenburg, “How to Save the Phenomena”: loc. cit., 114; *ibid.*, 132, n. 3. Kenneth Westphal, however, stresses that we should not go so far as to say that Hegel rejected forces or dynamical laws altogether: see his essay “Force, Understanding and Ontology,” *Bulletin of the Hegel Society of Great Britain* 57/58 (2008): 1–19, especially section 5 with n. 14.
- 95 *Sir Isaac Newton’s Mathematical Principles of Natural Philosophy*, ed. Florian Cajori, loc. cit., 547: “But hitherto I have not been able to discover the cause of those properties of gravity from phenomena, and I frame no hypotheses; for whatever is not deduced from the phenomena is to be called an hypothesis; and hypotheses, whether metaphysical or physical, whether of occult qualities or mechanical, have no place in experimental philosophy.”
- 96 G.W.F. Hegel, *Vorlesungen über Naturphilosophie Berlin 1825/26*, Manuscript Dove, l.c., 68 (“Wenn nichts physikalisch bestimmt werden soll, so wäre der Ausdruck ‘Kraft’ wegzulassen”). In other words, Hegel argues that describing motions in a way exemplified by the Keplerian laws (where exclusively spatio-temporal quantities occur) is preferable to using dynamical laws (that introduce unexplainable explanatory principles).
- 97 Cf. Heinrich Hertz, *The Principles of Mechanics Presented in a New Form*, trans. D. E. Jones and J. T. Walley (New York: Dover Publications, 1956), 11–12: “It cannot be denied that in very

- many cases the forces which are used in mechanics for treating physical problems are simply sleeping partners [Hertz's original expression is "leergehende Nebenräder," i.e., "needless auxiliary wheels"], which keep out of the business altogether when actual facts have to be represented. In the simple relations with which mechanics originally dealt, this is not the case. ... But it is otherwise when we turn to the motions of the stars. Here the forces have never been the objects of direct perception; all our previous experiences relate only to the apparent positions of the stars. Nor do we expect in future to perceive the forces. The future experiences which we anticipate again relate only to the position of these luminous points in the heavens. It is only in the deduction of future experiences from the past that the forces of gravitation enter as transitory aids in the calculation, and then disappear from consideration. Precisely the same is true of the discussion of molecular forces, of chemical actions, and of many electric and magnetic actions. And if after more mature experience we return to the simple forces, whose existence we never doubted, we learn that those forces which we had perceived with convincing certainty, were after all not real."
- 98 I wish to express my gratitude to Stephen Houlgate and to Ken Westphal for their thorough review of the original manuscript of this chapter.

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