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Colding, Ørsted, and the meanings of force

THE DANISH PHYSICIST and engineer Ludvig August Colding (1815–1888) is known to historians of nineteenth-century physics as the author of one of several formulations, during the 1840s, of the concept that eventually gained currency as the principle of the conservation of energy. Thanks largely to the work of Per Dahl, the substance of Colding's work and a rough idea of the route he followed has been known for several decades.[1] In brief, Colding sought experimental corroboration, in terms of the frictional heat produced via the expenditure of a measured amount of mechanical work, of a rough notion of the general imperishability of the forces of nature that he derived from an originally metaphysical conviction concerning the imperishability of the human spirit regarded as a species of force. Nor has the importance gone

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Research for this study was supported by generous grants from the Dibner Library Resident Scholar Program, Smithsonian Institution Libraries, for a month's work in Washington, and from The American-Scandinavian Foundation for three weeks' work in Copenhagen, both during the summer of 1995, without which this study could not have been undertaken. At the Smithsonian, Nancy Gwinn and Leslie Overstreet most facilitated my work; at the Royal Danish Academy of Sciences, Thor A. Bak and Pia Grüner provided both hospitality and assistance. To all of them I express my warmest thanks. I am deeply grateful to Thomas Söderqvist for boundless assistance and friendship during and after my stay in Copenhagen. I also thank Ole Knudsen for saving me from error in deciphering a Danish manuscript. With respect to a matter of convention, double quotation marks ("...") indicate direct quotations, while single marks ('...') call attention to words used in some qualified sense. The expression "Colding's paper of 18xx" refers to the paper *composed* in 18xx. An equals sign (=) connects the cited passage with its reprinting in one of the several editions of Ørsted's collected works or, in Colding's case, with its translation in Dahl's 1972 edition of Colding's papers. An "approximately equals" sign (~) indicates either another place of contemporary publication (for Ørsted often in a different language) of what is essentially or very nearly the same passage, or a translation in the English-language *Soul in nature* of 1852. A semicolon separates multiple references, some of which may in fact be reasonably close. These devices are intended to be a rough guide to Colding's and (especially) Ørsted's complex bibliography. Significant variants among otherwise similar passages are regularly noted.

1. Dahl 1963, 1972, 1978.

unnoticed of Colding's relationship to Hans Christian Ørsted (1777–1851), to whom Colding was attached for many years as student and protégé. Ørsted had disclosed the interactive relationship between electricity and magnetism in 1820 and was a highly visible proponent of the notion of the unity of nature, as showcased in particular in the collection of essays he entitled *The spirit in nature*.[2] Yet some of the important details in this overall picture remain unclear. The quality of Colding's metaphysical beliefs has not been explored in appropriate depth, nor has the significance been established of his brief reference to the role played in the development of his ideas by the antimaterialistic pronouncements of zoologist and physiologist Daniel Frederik Eschricht (1798–1863).[3] Nor have we been adequately enlightened as to the significance of what he referred to as d'Alembert's principle of lost forces, or to the status of such a principle in the mechanics of the period.[4] And his relationship to Ørsted is problematic. Although there would appear to be some important connection between Colding's and Ørsted's general views on nature and its forces, and Ørsted occasionally asserted some kind of unity among the forces of nature, he failed signally to appreciate the significance of Colding's work when it was given him to evaluate.[5] The solution to this apparent paradox will be sought through an understanding of Ørsted's changing conception of force and its relationship to the "activities" of heat, light, electricity, magnetism, and chemical activity.[6] Without paying proper attention to language, historians have tended to read back into Ørsted's usages meanings of "force" that came to it in large part as a result of the work of Colding and his generation.[7]

2. Ørsted 1850a, 1850c, 1850–51a. Although the work is generally known in English as *The soul in nature* (Ørsted 1852), "Aand" in Ørsted's title—or "Geist," as he himself translated it—is better rendered by "Spirit." As near as I've been able to determine, Ørsted never used the normal word for soul (*Sjæl, Seele*). Even when broaching the question of its continued existence after the death of the body, he referred to it as "det fri Fornuftvæsen" (Ørsted 1851b, 21). The closest I could find was a single passing reference to "den ubesjælede Natur" (25). Unless otherwise indicated, all translations in this paper are mine, although I have regularly consulted Dahl's translations of Colding's papers and sometimes adopted his wording. His renderings are often too free for my taste.

3. Colding 1856, 158 = Dahl 1972, 120.

4. Colding 1847(1849), 208; 1848(1850), 129 = Dahl 1972, 26; 1849(1850), 170 = Dahl 1972, 48–49 (in a paragraph omitted from Colding 1849[1871]); 1863(1864), 58 = Dahl 1972, 160; cf. Dahl 1963, 176; 1972, xviii–xix, 170n.32; 1978, 85.

5. Ørsted 1843(1920).

6. Although complete consistency is an unattainable goal, I have tried to render important terms by a single English equivalent: *Kraft* = force; *Virkning* (*Wirkung*) = action (or effect); *Virksomhed* (*Wirksamkeit*) = activity; *virksom* (*wirksam*) = active; *Aand* (*Geist*) = spirit; *aandelig* = spiritual (or intellectual); *almindelig* (*allgemein*) = universal (or general); *Sætning* = proposition; *uafhængig* = independent; *selvstandig* = autonomous; *Tanke* = idea (or thought). I have preserved contemporary Danish and German spelling.

7. Cf. Caneva 1997, 41, 49–53.

Having been introduced to Colding as a graduate student in the late 1960s, I had occasion to take a closer look at his and Ørsted's work in connection with a recent study of the influence of *Naturphilosophie* on physics. In 1957 Robert Stauffer made clear Ørsted's conceptual indebtedness to *Naturphilosophie* and two years later Thomas Kuhn placed Colding within its ambit.[8] Having written a book on *Robert Mayer and the conservation of energy*, I was intrigued by several striking similarities between Mayer and Colding, in particular the central role played in each man's conceptual odyssey by theologically grounded metaphysical musings concerning the indestructibility (with Mayer) or imperishability (with Colding) of forcelike spiritual entities, combined in each case with a subsequent search for empirical evidence for the quantitative equivalence of heat and mechanical work. In neither case was *Naturphilosophie* found to play a plausible role. It appeared to me that an analysis of Ørsted's usages, carried out in light of Colding's work on what he termed the imperishability of the forces of nature,[9] would enhance our understanding of each individual's work, their relationship to each other, and the meanings of force in general during the first half of the nineteenth century. The last section of this paper addresses these and other wider historiographical issues. The bulk of the paper, however, consists of analyses of Colding's life and relationship to Ørsted; of what Colding accomplished vis-à-vis the conservation of energy; of the complex meanings of the various components that constituted his reconceptualization of forces; of responses to Colding's work by two of his former professors, Ørsted and mathematician Christian Ramus (1806–1856); of Ørsted's changing understanding of the forces of nature; and, finally, of Ørsted's deep conviction of the rational unity of man and nature. More broadly, I hope in this study to contribute to an understanding of the process of concept formation in science.

1. COLDING AND HIS ACHIEVEMENT

The formative years

Colding was born in 1815 near Holbæk, in north-central Zealand (the island on whose northeast corner lies the city of Copenhagen), where his father, Andreas Christian Colding (1780–1836), had purchased an estate after retiring as a ship's captain.[10] His mother, Anna Sophie Fønns (1778–1844),

8. Stauffer 1957; Kuhn 1959.

9. Colding's tombstone in the Assistens Kirkegård in Copenhagen bears the simple inscription "Naturkræfterne ere uforgjængelige." Even long after the general acceptance of the conservation of energy, physicist Edvard Sextus Johansen (1879–1954) (1915, 3) identified Colding's "epoch-making results" as "his experiments concerning the imperishability and transformation of forces."

10. See Marstrand 1929, 7–19 for a wealth of information on Colding's family and early life.

was the daughter of a prominent Lutheran clergyman.[11] His elder brother and only sibling, Peter Andreas Colding (1813–1886), obtained a theology degree in 1843 and served as pastor in a number of small Danish towns. Although Ørsted was from the small and rather remote island of Langeland, he had family in Holbæk and had become acquainted with Colding's father while the son was a young boy. Ørsted advised Colding to apprentice himself in 1836 to A.C. Olsen, a master cabinet-maker in Copenhagen who also taught drawing at the Academy of Art.[12] The task of preparing drawings, under Olsen's direction, of steam engines for the Royal Mint in 1837 seems to have been the catalyst for Colding's interest in machines, though Vilhelm Marstrand has emphasized the widespread attention given to the many new machines then gaining prominence: not only steam engines and their offspring, steamships and railroads, but also spinning machines and gasworks seemed to hold out the promise of social improvement through science and technology.[13] Desiring to pursue this interest seriously at the Polytechnic School in Copenhagen (*Den Polytechniske Læreanstalt*)—of which Ørsted had become the first director in 1829—he again followed Ørsted's advice first to study for the general preparatory examination, then for the entrance examination to the Polytechnic School, both of which he passed in 1837.

Ørsted, who was also professor of physics at the Polytechnic, continued to guide and encourage Colding through formal instruction and private conversation, and Colding received a solid education in engineering. On the basis of his written examination in mechanics on April 5, 1841, Colding received the grade "laudabilis prae caeteris" in drafting and specimen drawings, "laudabilis" in the practical exercise in theory of machines (*Maskinlære*), differential and integral calculus, advanced mechanics, mathematical physics, chemistry, and technology, "haud illaudabilis" in descriptive geometry, chemical physics, and theory of machines (written), and "non contemnendus" in the application of calculus to geometry.[14] Among the professors whose signatures attested his performance were Ørsted and Ramus. After graduating as

11. On the spelling of Colding's mother's name, see the errata in Marstrand 1929, [63].

12. These and other details to follow derive from Marstrand 1929, 17–19; Dahl 1963, 175–177; 1972, xiii–xv; 1978, 84; Hansen and Vinding, 1979, 466. Marstrand (1929, 18), Dahl (1972, xiv), and Hansen and Vinding (1979, 466) all give the date as 1836, though the entry under Colding's name in the examination protocol says 1835 (Polytechnisk Læreanstalt 1831-58[MS], 77).

13. Marstrand 1929, 19–20.

14. Polytechniske Læreanstalt 1831–58(MS), 77. On the oral part of the examination he received the grade of "laudabilis prae caeteris" in differential and integral calculus, "laudabilis" in algebra, the application of calculus to geometry, advanced mechanics, technical mechanics, theoretical chemistry, and descriptive geometry, and "haud illaudabilis" in theory of machines, chemical technology, chemical physics, mathematical physics, and technology, earning the *Hovedcharacter* of "haud illaudabilis" (ibid.).

"polytechnisk Candidat i Mechanik," Colding worked for a time as a private tutor, delivered a series of lectures on mechanical and chemical physics under the auspices of the Society for the Propagation of Science (*Selskabet for Naturlærens Udbredelse*, founded by Ørsted in 1824) in Nakskov on the western end of Lolland during the winter of 1841–42, and, returning to Copenhagen, held several teaching positions in mathematics and drafting before being appointed Inspector of Roads and Bridges in Copenhagen in July 1845, a position he held with distinction until retiring in 1886.

While still a student during the winter of 1839, Colding had begun to give Ørsted significant assistance with his long-term investigation of the compressibility of water, begun in 1818.[15] Ørsted reported in 1826 that "[i]n so far as I have tried the temperature of compressed water (to forty-eight atmospheres) *no heat is liberated by its compression.*"[16] Deviations reported by others suggesting that water is not uniformly compressible, but becomes less so the warmer it is, prompted him to return to the issue in 1832. Preferring a universal law for the compressibility of water valid at all temperatures, Ørsted argued—despite his earlier experimental finding—that the apparent deviations from uniformity could be accounted for by assuming that the temperature of water rises 1/40°C for every atmosphere of pressure.[17]

Ørsted enlisted Colding's experimental and computational assistance in 1839 to effect "a direct demonstration of the generation of heat by compression by means of a thermocouple."[18] When Ørsted finally reported his results to the Royal Danish Academy of Sciences (*Det Kongelige Danske Videnskabernes Selskab*) in 1845—revising his earlier figure to 1/49.2—he acknowledged that Colding had performed the numerous experiments and carried out all the calculations.[19] In the introduction to the Danish edition of his textbook, *The mechanical part of physics* (1844), Ørsted reported that an unnamed former student was assisting him with the anticipated (but in the end unachieved) publication of a work devoted to heat theory; it seems reasonable to suppose that that person was Colding.[20] Ørsted's central concern seems to have been to save the uniform compressibility of water: the production of heat

15. Dahl 1963, 175; 1972, xix.

16. Ørsted 1826(1827), 202 = 1920, *2*, 336; Meyer 1920a, cxxvi–cli.

17. Ørsted 1833, 16 = 1920, *2*, 486; 1833(1834), 361 = 1920, *2*, 399; Meyer 1920a, cli–clii. Cf. Ørsted's undated letter, sometime after May 1829, to Christian Samuel Weiss (1780–1856) in which he was concerned to distinguish the expansive force of heat from a resistance to compression proper to matter as such (Harding 1920, *1*, 329–330).

18. Meyer 1920a, cliii–cliv, on cliv; Dahl 1972, xx–xxi. Meyer reported that "Colding wrote a small treatise on the result which is found among Ørsted's papers, but he did not get to any decisive result and so Ørsted has probably not been willing to publish it" (cliv). I have not been able to locate this treatise.

19. Ørsted 1845(1846), 117 = 1920, *2*, 527–528.

20. Ørsted 1844, v.

through compression does *not* necessarily imply any conception of the transformation of mechanical work into heat. Nevertheless, it is likely that Colding's developing speculations inclined him to make such a connection. Their use of a thermocouple may also have contributed to his growing sense of the transformability of one force into another.[21]

Be that as it may, it appears that Colding had begun to ponder the question of the nature of force on general philosophical grounds sometime around 1839.[22] Expressing to Ørsted his intention of presenting his ideas at the July 1840 meeting of Scandinavian scientists in Copenhagen, he was advised to wait until he had obtained experimental support for his ideas, toward which end Ørsted arranged for him to receive financial assistance from the Society for the Propagation of Science.[23] On November 1, 1843, Colding presented his results to the Academy of Sciences in a paper, his first, entitled "Some propositions concerning forces." Postponing for the time being an examination of the various insights and inspirations that lay behind Colding's theoretical work, let us examine the series of papers he composed over a span of twenty-one years in order first to assess what he said that looks to us like conservation of energy.

Colding's earliest researches

Colding's paper of 1843, which remained unpublished until 1856, opened with the admission that although we neither know nor can we comprehend

21. Dahl (1972, xix) urged the significance of Colding's work with Ørsted on the compressibility of water.

22. With reference to his work of 1843, Colding (1863[1864], 58 = Dahl 1972, 160) reported that he had had the idea of the "principle of the perpetuity of energy"—as it was expressed in the anonymous 1864 translation published in the *Philosophical magazine*—"nearly four years before." This appears to have been the source for Dahl's (1978, 85) dating of Colding's insight to 1839. Writing in 1848, Colding (1848[1850], 131 = Dahl 1972, 27) reported that he had devoted himself to the question of the imperishability of forces "already for nearly half a score of years." Without citing a source, Marstrand (1929, 19) gave a date of 1840. For Dahl (1978, 85), "Colding apears to have compounded the energy principle from a complex merger of metaphysical speculation and experiment."

23. Colding 1856, 139 = Dahl 1972, 107; 1863(1864), 58 = Dahl 1972, 160–161; Marstrand 1929, 21–22; Dahl 1963, 176–177; 1972, xxiv; Hansen and Vinding, 1979, 466, 468. Ørsted's advice to Colding exactly paralleled that which he had given around 1810 to another student and protégé, Johannes Carsten Hauch (1790–1872), who recalled Ørsted's response when he noticed that young Hauch appeared to be more interested in general reflections on nature than in detailed empirical investigations: "It is also my firm conviction...that a great fundamental unity runs through all of nature, but just when one has convinced oneself of this, it becomes doubly necessary that one fix one's attention on the world of the manifold, in which this truth can only then find its corroboration. If one does not do this, unity itself remains a barren and empty thought that leads to no true insight" (Hauch 1852, 120; translation adapted from Meyer 1920a, xlvi).

what constitutes the essence of a force, we can know forces in terms of their effects.[24] Alluding to a situation he would later associate with what he termed d'Alembert's principle of lost forces, Colding noted that motive forces acting on a material point without being in equilibrium produce a quantity of motion corresponding to the active force. This quantity of motion is then communicated to the surrounding material "such that the originally communicated quantity of motion is distributed within a short time to such a large mass that any sensible trace of this activity has disappeared."[25]

> But it does not appear to me that one has any grounds for supposing that an activity can gradually be lost in the corporeal [world] without in any way appearing sensibly active in its original magnitude; it seems to me even much more to be grounded in the nature of the matter that the forces that sensibly disappear must again appear as active in other ways. This idea arose with me a long time ago, and I have never been able to reject it.

He thus advanced as "a universal [*almindelig*] law of nature" the proposition that "When a force sensibly disappears, it only undergoes a change in form and remains thereafter active under other forms."[26] Although he had so far neglected to define just what he meant by "force," his further gloss on this law made it clear that he was thinking principally about motive forces and heat, but also about electricity and as-yet unspecified other agencies:[27]

> It is well known that in reality, too, there always appear other forces where some disappear, such as electricity, heat, etc. If, therefore, this proposition concerning lost activities [*tabte Virksomheder*] is correct, it will—so it appears to me—stand as an appropriately connecting link between the known propositions concerning the various forces of nature. I will, for example, assume that the entire effect [*Virkning*] that is lost in time t by a certain motive force [*bevægende Kraft*] can be designated by q; then the new activity must be equal to q, and since, with the loss of motive forces, this can in the main be set equal to the thermal effect [*Varmevirkning*], then the thermal effect must be equal to q.

24. Colding 1843(1856), 3 = Dahl 1972, 1.

25. Colding 1843(1856), 3 = Dahl 1972, 1 (both quotes).

26. Colding 1843(1856), 4 = Dahl 1972, 1: "Naar en Kraft sandseligt forsvinder, da undergaaer den blot en Formforandring og bliver derpaa virksom under andre Former." He quoted himself in Colding 1845(MS), 2 and in 1848(1850), 132 = Dahl 1972, 29.

27. Colding 1843(1856), 4 = Dahl 1972, 1–2. Parts of the first and second sentences were quoted (the latter with minor changes) in Colding 1845(MS), 2: "'at der i Virkeligheden ogsaa stedse fremkommer andre Kræfter hvor nogle forsvinde'" and "hvis 'denne Sætning om tabte Virksomheder er rigtig, vil den staae som et temmeligt forbindende Led imellem de bekjendte Sætninger om de forskjellige Naturkræfter.'" He again quoted the first phrase in Colding 1848(1850), 132 = Dahl 1972, 29; he there also quoted the third sentence (with minor changes).

Recognizing that only experience can decide the correctness of this law, Colding reviewed the relevant literature. He cited Dulong's important finding "that equal volumes of all elastic fluids, at the same temperature and pressure, release or absorb the same quantity of absolute heat when they are suddenly compressed or expanded by the same fraction of their volume."[28] That such compressions require the same "force" confirmed his law, though Colding apparently did not see how to use this and other information pertaining to gases to derive a number representing the equivalence between heat and work, as Mayer did. He further cited Ørsted's and others' finding that the compression of water produces heat, and a number of qualitative and crudely quantitative reports of the generation of heat when solids are subjected to a variety of physical processes. Although Rumford's experiments provided little useful data, Colding noted that Rumford had concluded "that heat is not a distinctive substance, but that it must consist in a motion."[29] Nevertheless, since published results were incapable of corroborating his proposed law with any precision, he undertook a series of experiments himself "with the encouragement of *Conferentsraad* Ørsted."[30]

Those experiments involved measuring the frictional heat produced by dragging a sled variously loaded with cannonballs along rails of different metals, a setup Colding adapted from Coulomb. The expansion of the rails together with other experimental data on the thermal expansion of metals gave him a measure of the heat produced, and a dynamometer attached to the sled as it was pulled gave him a measure (in pounds) of the motive force exerted. This paper does not indicate that Colding had any precise concept of mechanical work, and the distance over which the motive force operated disappeared unmentioned in his ratios as a factor constant for every trial. His task was "to derive the law according to which the frictional heat depends on the lost force."[31] He first reduced both sets of measurements—"the frictions, i.e., the lost forces" and the "quantities of heat"[32] —to convenient comparative units, then calculated the ratios between these values for the several series of experiments. For example, for his three series with brass rails he found the ratios between the lost forces to be 2.75:1.79:1, while the ratios between the quantities of heat produced were 2.77:1.83:1. On the basis of such results he concluded that "the quantities of heat produced in all these cases are proportional

28. Colding 1843(1856), 4 = Dahl 1972, 2. In quoting from Dulong 1828(1831), 188, Colding changed "quantité absolue de chaleur" to "Mængde af absolut Varme."

29. Colding 1843(1856), 5 = Dahl 1972, 3.

30. Colding 1843(1856), 6 = Dahl 1972, 3. Those experiments were carried out at the end of 1842 and in 1843 (Colding 1845[MS], 1).

31. Colding 1843(1856), 16 = Dahl 1972, 11.

32. Colding 1843(1856), 17 = Dahl 1972, 12: "Frictionerne, ɔ: de tabte Kræfter" and "Varmemængder."

to the lost motive forces."[33] In the paper's concluding three paragraphs he extrapolated his results to other forces and applied his newly confirmed proposition—now expanded without clear warrant to assert not just the proportionality between the lost and the subsequently manifested forces but also their equality—to the issue of perpetual motion machines:[34]

> Since all the earlier well-known experiments on the production of heat via the loss of motive forces, as well as all the experiments I performed concerning the ratio of the frictional heat to the lost force, seem very satisfactorily to confirm the proposition concerning lost motive forces that I proposed at the beginning of this paper—namely that when a force sensibly disappears it only undergoes a change in form and remains thereafter active under other forms—one will not then object to my assuming that precise experiments will demonstrate the correctness of this proposition in the most complete manner.
>
> But it is not only for motive forces that I assume this proposition to be valid; I believe one should declare it to be universally valid for all forces, as for example when opposing chemical forces annihilate [*tilintetgøjre*] each other's effect [*Virkning*], since in reality the force is only annihilated in form, but appears in its original magnitude under other forms.
>
> If one does not assume this, I do not quite know how one can explain in a great many cases what nature exhibits; but with regard to the complete proof of the impossibility of a perpetuum mobile this proposition appears so urgently necessary that without it every such proof should be regarded as false. Thus if one imagines a motive force applied in an advantageous manner to such a machine, one then obtains therewith not only a certain quantity of motion, but there also appear other active forces such as electricity, heat, etc.; but if one had now arranged the whole such that these forces could also be collected and employed advantageously to produce motion, one can then ask whether the effect so obtained would not be capable of producing a greater effect than the original force. Here there is clearly just as great a reason to expect a greater effect as a lesser if one will not assume that precisely the same [effect] would thereby appear, and one thus sees that if one does not assume the proposed proposition as correct, then neither can one decide whether one will ever succeed in constructing a perpetuum mobile.

Colding clearly overreached himself in his conclusion, at least as far as his experimental warrant went. His disproof of the possibility of a perpetuum

33. Colding 1843(1856), 17 = Dahl 1972, 12.

34. Colding 1843(1856), 19–20 = Dahl 1972, 13–14. The first sentence of the second paragraph was quoted with minor changes in Colding 1845(MS), 2: "'saa at for Exempel naar chemiske Kræfter tilintetgjøre hinandens Virkning, da er i Virkelighed Kraften kun i Formen tilintetgjort, men fremtræder i sin oprindelige Størrelse under andre Former.'" He again quoted himself in Colding 1848(1850), 132 = Dahl 1972, 29. The last paragraph reappeared in a slightly edited version in Colding 1847(1849), 216; he quoted the second clause of the paragraph's first sentence in Colding 1848(1850), 132 = Dahl 1972, 29.

mobile is based solely on rational grounds: *unless* one assumes that forces that undergo change in form remain unchanged in magnitude, however that might be defined and determined, *then* one cannot be certain of the impossibility of constructing a perpetuum mobile. So far both his experiments and his language addressed only the question of the *disappearance* of force, not also that of its possible *creation.* The "forms of force" he had considered included motive force, heat, electricity, and chemical forces, though with some terminological wavering between "force" (and "lost forces") and "activity" (and "lost activities") and without a clear sense that the (lost) "motive force" is not by itself meaningfuly comparable to the heat generated. The gratifying correspondence of his ratios obscured the weakness of his conceptual grasp.

In his earliest discussion of "the impossibility of a so-called perpetuum mobile" in 1809, Ørsted had considered only the motion of mechanical devices subject to unavoidable resistances, arguing further—with no concern for units of measurement—that one body cannot communicate motion to another without losing an equally large motion, nor can one body increase its motion without taking it from another.[35] His treatment of the topic in his text of 1844, *The mechanical part of physics*, repeated that reasoning, then extended its applicability to other-than-mechanical systems:[36]

> But since no moved body can communicate another and greater quantity of motion than it itself has (cf. §85), within the machine there can be no replacement made for what is lost in conjunction with the resistance of the air or of friction, or with the resistance of bending....Nor in the natural laws for the equilibrium and motion of liquids and gases is there found anything that constitutes an exception from the stated fundamental law, and as a consequence of the nature of the matter there could be found none....
>
> The idea of a perpetuum mobile presupposes, then, that the force that is supposed to replace the loss in conjunction with the obstacles to motion is produced from nothing. If it is supposed still to do work, the force necessary for it must also be produced from nothing. Those who in recent times characterize

35. Ørsted 1809, 212–213, on 212.

36. Ørsted 1844, 268–269; 1851a, 270–271 (which has "*Kraftvermehrer*" and "die wieder als bewegenden [sic] Kraft wirkte," and with the curious omission of the second sentence of the second paragraph from the German edition). The cited §85 recognized the impossibility of increasing the work a machine can perform by transforming the high-speed but small forces that drive it into slower but stronger effects: "The great effects that one can thus produce with very small forces that have an appreciable speed have often misled the uninformed into believing that there took place an actual increase in force [*Kraftvinding, Kraftgewinn*]; but one will have seen from the foregoing that the applied force and the quantity of work produced are always equal, or, more correctly, that the latter, due to the impediments to motion, is somewhat less, and at the same time one easily perceives that the old proposition, that *what one gains in force is lost in time*, is only another expression for the same idea and is only valid to the same extent" (55 *bzw.* 58, translating the latter's "die angewendete Kraft" instead of the former's "Kraftanvendelsen").

> their striving after a perpetuum mobile by saying that they are searching for a multiplier of force [*Kraftformerer*] are using a quite correct expression; but with it the absurdity is also immediately indicated.
>
> One could conceive of a perpetuum mobile otherwise than heretofore, and imagine the problem of producing in the machine heat, electricity, magnetism, or some other force still unknown to us, which could act to produce motion [*som kunde virke bevægende*]. As far as our knowledge reaches, we also see in these forces the same strict laws for the relationship of the magnitudes as in the theory of motion; but the present boundaries of our knowledge do not permit a strict proof for the impossibility of the solution of this problem.

It is very possible that Colding was exposed to such considerations through contacts with Ørsted, in which case he would likely have seen himself as supplying the proof Ørsted said was lacking. On the other hand, given the date of Ørsted's book—its preface was dated September 24, 1844—Ørsted may have been reacting to Colding's paper of November 1843. But Ørsted regularly repeated the same points in virtually the same words over many years, and it is not unlikely that his text gives a fair representation of the lectures he had been giving for several decades.

Searching for connections with others' work

The committee of the Academy appointed to report on Colding's work, which consisted of Ørsted, Ramus, and Johan Christopher Hoffmann (1799–1874), recommended on January 4, 1844 that he be awarded 200 *Rigsbankdaler* to pursue his experiments.[37] By October 1845 his new instrument was not yet ready, but he presented the theoretical results he had arrived at in the meantime on the basis of his original proposition in a long and never published paper.[38] Its title, "On the loss of forces," testifying to Colding's ongoing search for appropriate language, it remained for the most part conceptually within the bounds of his earlier reflections as it sought support from others' experimental findings and struggled toward a more coherent understanding of force. Its opening paragraphs repeated his attention to what might be called the ontology of mechanical interactions and the importance of his dispositional conviction in the intrinsic irrationality of the notion that an "activity" might disappear without effect:[39]

37. Ørsted, Ramus, and Hoffmann 1844(1845), 3; see the Bibliography for additional locations. Hoffman taught physics and chemistry at the Military Academy (*Den Militære Højskole*).

38. Colding 1845(MS), of 89 pages.

39. Colding 1845(MS), 1:

Naar [to (*crossed out*)] bevægende Kræfter, som kun tildeels ophæve hinanden, virke paa et materielt Punkt, saa frembringer Resultanten en Bevægelse af det materielle Punkt, der derved erholder en Bevægelsesmængde, som fordeles paa de materielle Dele dette træffer under Bevægelsen. De Dele som saaledes have erholdt en Bevægelsesmængde meddele paa samme

> When [two (*crossed out*)] motive forces that can only partially neutralize each other [*ophæve hinanden*] act on a material point, the result produces a motion of the material point, which thereby acquires a quantity of motion that is distributed to the material parts it encounters while in motion. The parts that have thus acquired a quantity of motion communicate it in the same fashion to the surrounding material parts, and this continues without cease.
>
> Since, as a consequence of this, the applied quantity of motion is continuously more and more dispersed, it is obvious that the applied activity's moment [*Betydning*] as quantity of motion soon disappears, and insofar as this is the only form of action of the applied force, its moment as active cause must thereby disappear.
>
> But that an activity should be able to disappear in the corporeal world without again appearing as active cause, that seems to me to conflict with what reason demands.
>
> It is this idea that has provoked in me the desire to investigate this relationship more closely, and it is with the feeling that this idea cannot possibly be incorrect that, for several years already, I have with intense delight sacrificed a large portion of my free time to contemplating and reflecting on the correctness of it.

After repeating the principal claims from his earlier paper, Colding noted the additional support his views received from Hess' experiments on heat produced during chemical reactions, which he had only later become acquainted with.[40] In a reply to a potential criticism, an objection likely raised by Ørsted, he addressed the possibility that one activity might simply arouse (*opvække*) another instead of undergoing a change in form:[41]

Maade denne til de omgivende materielle Dele og dette vedbliver unden Uphór.

Da de anvendte Bevægelsesmængde, som Fólge heraf, bestandig mere og mere adspredes, saa er det indlysende, at den anvendte Virksomheds Betydning som Bevægelsesmængde snart er forsvunden og saafremd denne er den anvendte Krafts eneste Virkeform, maa dens Betydning som virkende Aarsag dermed forsvinde.

Men at en Virksomhed skulde kunne forsvinde i det legemlige uden igjen at fremtræde som virkende Aarsag, det forekommer mig at staae i Strid med hvad Fornuften tilsiger.

Det er denne Tanke som hos mig har fremkaldt Lysten til nærmere at undersóge dette Forhold, og det er med Fólelsen af, at denne Tanke umulig kan være urigtig, at jeg alt i flere Aar med inderlig Glæde har opoffret en stor Deel af min Fritid til at betragte og overveie Rigtigheden heraf. The first three and the fourth paragraphs are close, respectively, to Colding 1848(1850), 129, 130–131 = Dahl 1972, 26, 27, the last of which (quoted at note 69) more expansively describes his "idea" as concerning "the forces' imperishability and their continual activity." For his own earlier statements see the passages quoted at notes 25, 26, and 34.

40. Colding 1845(MS), 2. Germain Henri Hess (1802–1850) published a long series of thermochemical investigations in Poggendorff's *Annalen der Physik und Chemie* between 1839 and 1842 in which he demonstrated that the net heat produced during a series of chemical reactions depends only on its endpoints, not on the path taken.

41. Colding 1845(MS), 3: "[O]m det ogsaa kan ansees for afgjort at enhver nye Virksomhed som fremkommer staaer i Forhold til den tabte Kraft, saa kan det ved fórste Øiekast synes, som om min Paastand, at det netop er den tabte Kraft, der fremtræder under andre Former, ikke derved

> [E]ven though it can be regarded as settled that every new activity that appears is proportional to the lost force, so might it at first blush seem as if my assertion, that it is precisely the lost force that appears under other forms, was not thereby sufficiently proven, but that one might possibly assume that the lost force merely aroused another, but itself disappears. Now it is to be sure the case that the new activity is produced, but it cannot be denied, either, that the inner activity that constitutes the essence of the produced activity—whether heat, electricity, etc.—is communicated at the expense of the activity that the communicating body had; but if one concedes that the activity is communicated, then at the same time one concedes that the cause of the effects of heat and electricity, etc., can be communicated, or that the forces are the same, but the mode of action or the form is different.

That Colding's reasoning on this important issue is less than compelling indicates the difficulty of grounding *a posteriori* a principle granted *a priori* validity. The experiences in question in no way yet entailed the correctness of his theory of forces (or activities); it was rather his theory that provided a touchstone for their interpretation.

The remainder of Colding's unpublished paper of 1845 was an elaborate mathematical development of his theory that made its first public appearance on July 12, 1847, in a paper Colding presented at the fifth meeting of Scandinavian scientists in Copenhagen, "On the universal forces of nature and their mutual dependence," a title he was to give with minor variations to three other, different, papers. Published in 1849 in the proceedings of the meeting, this was the first of his papers to see the light of day.

Colding opened with a more extended glimpse of his early reflections than he had previously offered:[42]

> In reflecting on d'Alembert's well-known principle concerning lost motive forces it first became clear to me that, whereas by this principle one understands by lost forces only the portions of the applied forces that are lost for the

var tilstrækkeligt beviist; men at man muligt maatte antage, at den tabte Kraft blot opvækkede en anden, men selv forsvinder. Vel er det nu saa, at den nye Virksomhed frembringes, men det kan heller ikke negtes, at den indre Virksomhed som udgjór Væsenet i den frembragte [Virksomhed, hvad enten det er (*interpolated above line*)] Varme, Electricitet o.s.v. er meddeelt paa den Virksomheds Bekostning, som det meddelende Legeme havde; men indrómmes det, at Virksomheden meddeles, saa indrómmes det med det samme, at Aarsagen til Varmevirkningerne og Electricitetsvirkningerne o.s.v. kan meddeles, eller at Kræfterne ere de samme, men Virkningsmaaden eller Formen er forskjellig." This passage is very similar to Colding 1847(1849), 215–216 and 1848(1850), 130 = Dahl 1972, 27, in which later versions Colding expanded the set of newly produced activities to include mechanical and magnetic activity and changed *Kræfterne* in the last sentence to *Grundkræfterne*. "Mode of action" and "form" were terms Ørsted regularly applied to forces and their manifestations.

42. Colding 1847(1849), 208. Dahl appears not to have known of this paper. This paragraph is very similar to Colding 1848(1850), 129 = Dahl 1972, 26.

> intended effect, in reality there takes place everywhere material resistances are present another completely determined loss of motive forces when a body is moved by means of a communicated mechanical activity.

Colding went on in accustomed fashion to follow the communicated activity as its quantity of motion dispersed itself among the material parts successively encountered. Thus the originally applied motive force would appear to have lost its moment (*Betydning*) as an active cause. But, as before, the idea that an activity might just disappear from the material world appeared to him absurd (*fornuftstridig*), hence he affirmed that "forces, without exception, only undergo a change in form when they seem to disappear, and appear again thereafter as active causes with the same magnitude but in changed forms."[43]

He illustrated this principle with an expanded set of examples: the production of heat, electricity, "etc." through friction when a motive force is applied to move a mass along a track; the reduction in temperature when a gas expands with no influx of external heat; the production of heat, "etc." when a gas or liquid is compressed; the production of heat, magnetism, "etc." when opposite electricities unite; and the appearance of unspecified other forms of force when (electrically) opposite chemical substances unite. This spate of etc.'s suggests that Colding was not prepared to claim as much as he was prepared to imply. Abandoning phenomenological language (one force disappears, another appears in its place), in his next and last example Colding for the first time spoke in explicit terms of a transformation of activity: "Since the magnetoelectric current appears with the action [*Indvirkning*] of a moved magnet on an electric conductor, it can be concluded that it is the mechanical activity that is transformed into [*der overgaaer i*] magnetoelectric activity etc."[44]

The preliminary experiments he had been able to perform with his improved apparatus—a fuller accounting would, he promised, soon be submitted to the Academy—followed the pattern of his earlier trials, but now his data allowed him to assert more than that "the quantities of heat produced are proportional to the lost activities."[45] Assuring himself that equal quantities of heat were produced in both the metal bars attached to the tracks and those attached to the sled's runners and that the speed of the sled had no influence on the heat produced, he combined his data—on the length, mass, and thermal expansion of the track bars and on the force required to pull the sled over its 4.11-foot path—with commonly accepted values for the expansion coefficients

43. Colding 1847(1849), 208–209, little changed in Colding 1848(1850), 129–130 = Dahl 1972, 26.

44. Colding 1847(1849), 209. All of these examples are cited in much the same language in Colding 1848(1850), 130 = Dahl 1972, 26–27.

45. Colding 1847(1849), 212.

and specific heats of the metals employed in order to derive what he termed "the mechanical activity that is equivalent to the unit of quantity of heat," that is, the heat necessary to raise the temperature of one pound of water 1° Celsius. He found that "1 lb. of water heated 1° Celsius = 1185 ft.-lbs."[46] In English units that works out to 678 ft.-lbs. per B.T.U., against a modern value of 778.

Before moving on to the mathematical portion of his paper, Colding picked up the thread of the theoretical considerations with which he had begun:[47]

> The proposition that when an activity disappears there appears therewith another of the same magnitude will in what follows be proven still further to be in agreement with experience as one comes to see that the results that are consequences of this proposition are found again in nature; but that my first fundamental idea [*Grundtanke*], that the forces are the same only appearing under changed forms, is also correct, that seems to me also true.

It would appear that Colding regarded the first formulation, in its modest phenomenological dress, as safer than the assertion of an underlying identity of essence. He revisited the anticipated objection that one activity might simply arouse another instead of undergoing a change in form and replayed his argument that only on the basis of his proposition can the impossibility of a perpetuum mobile be demonstrated.[48] He then proceeded to the more technical portion of the paper, where, he announced, he would derive a number of results from his new principle and demonstrate that it allows the mathematical treatment of many problems that earlier could only be decided by experiment, while at the same time the agreement of those results with experience serves to prove the correctness of that principle.

The first of the four sections devoted to mathematical elaborations was headed "General determination of the expression for the lost activity when a material point is subjected to arbitrary [*hvilkesomhelst*] mechanical forces."[49] Without explicitly introducing the concept of work and without alluding to his

46. Colding 1847(1849), 215. For "ft.–lb." Colding here used the ideogram for "lb." followed by a superscript "Fod," which he read "Pund Fod." From his own figures—4.11 Danish foot = 1.290 meters (Colding 1847[1849], 212; 1848[1850], 143 = Dahl 1972, 42) and 1364.4 English foot–pounds = 1325.0 Danish foot–pounds (Colding 1851[1852], 28 = Dahl 1972, 97)—one can calculate that 1 Danish foot = 1.030 English foot = 0.314 meter and 1 Danish pound = 1.000 English pound = 0.454 kilogram. Note that Colding elsewhere often represented foot–pounds by means of the ideogram for "lb." followed (as in English usage) by the superscript stroke for foot (′). Dahl consistently misread that symbol as simply "pounds," as in the example just cited at Dahl 1972, 97.

47. Colding 1847(1849), 215; cf. Colding 1848(1850), 130 = Dahl 1972, 27.

48. See the passages quoted at notes 41 and 34, resp.

49. Colding 1847(1849), 216.

gradual realization that one must consider the path over which a force acts in determining its (lost) "activity," Colding asserted that "the lost activity's increase is equal to the lost force, multiplied by the length of the path traversed in that moment."[50] By "lost force" he understood the mathematical expression for the portion of the applied forces that does not contribute to an increase in the velocity of the material point. The resulting "lost activity" he then showed depends solely on the forces of resistance in the direction of the point's path and equals the integral of those forces over the length of the path. If the force of resistance is constant and the integration constant eliminated in the usual fashion, "the lost activity is equal to the product of the friction and the space traversed" independent of the velocity.[51] Thus did Colding find theoretical corroboration for his experimental results. In a flurry of mathematical manipulation in the section headed "The development of heat accompanying the motion of aeriform bodies," Colding rederived the formulas of Dulong, Holtzmann, and Clapeyron pertaining to thermal properties of gases (the latter two from versions published in the *Annalen der Physik und Chemie* in 1848 and 1843). These derivations involved what he still called the lost activity.[52] Although silent here about possible experimental confirmation, Colding nicely exhibited the theoretical range of his developing theory.

Turning to the question of "The development of heat accompanying the motion of liquids [*draabeflydende Legemer*]," he derived a formula from which he calculated that an increase of one atmosphere should raise the temperature of water in Ørsted's experiments on its compression by 1/36.57°C. He asserted that this value agrees closely with Ørsted's experimental findings, which he did not, however, cite.[53] (As mentioned earlier, Ørsted had reported a figure of 1/49.2.) After calculating corresponding numbers for four other liquids without being able to compare them to any experimentally derived values, he calculated the "mechanical activity" capable of raising the temperature of one pound of air by one degree Celsius. Using a conversion factor determined by De La Roche and Berard, he showed that the figure for air of 321.417 ft.-lbs. is equivalent to a mechanical activity for water of 1204.287 ft.-lbs., which is the same result obtained by substituting the previously calculated thermal coefficient for the compression of water into another formula from a previous section. This number, he urged, deviates only slightly from his experimentally determined value of 1185 ft.-lbs.

50. Colding 1847(1849), 217.

51. Colding 1847(1849), 219.

52. The 1848 date of Holtzmann's paper indicates that the version of Colding's paper published in 1849 was not exactly the same as the one read in 1847.

53. Colding 1847(1849), 231. Colding here also made use of results he had derived in an earlier section, "General determination of the expression for the lost activity accompanying the motion of a fluid" (220–222).

Colding sought to apply his results to calculate the specific heat of air as a function of altitude and thence the quantity of heat contained by a unit mass of another heavenly body's atmosphere. He then calculated that the difference in the quantity of heat between a unit mass of the sun's atmosphere near the sun's surface and one at the outer reaches of the solar atmosphere is 214,020 times as great as that difference for a unit mass of the earth's atmosphere. Without explaining his reasoning further, he closed this paper with his implied solution to what Herschel had called "the great secret," the source of the sun's heat and light: "The principle set forth thus leads to the recognition of the cause of the great heat and light activity that the sun contains; indeed, it seems to show that, just as it is the universal attraction that holds all the heavenly bodies in their places, so too it is the universal attraction that determines the enormous heat and light activity with which the sun acts on the planets."[54]

It is not clear from Colding's discussion whether he appreciated the necessity of taking into consideration what we call potential energy—what Mayer termed "fall force"—or how precisely he imagined the production of heat and light to take place. From a modern standpoint he had not yet achieved a full accounting of the interrelationships among the various "forces" of nature, nor introduced a clear and consistently deployed terminology with regard to "forces" and "activities," "lost" or otherwise. Nevertheless, Colding had clearly obtained appreciable experimental and theoretical corroboration for his proposition that "forces, without exception, only undergo a change in form when they seem to disappear, and appear again thereafter as active causes with the same magnitude but in changed forms."

Colding re-presented the experimental and conceptual aspects of his work to the Academy on March 3, 1848, now expanded by way of appreciable quotation from relevant published work of Liebig, Jacobi, and Faraday. Published separately in 1850, "Investigations concerning the universal forces of nature and their mutual dependence and especially concerning the heat developed by the friction of certain solid bodies" exhibited Colding's desire to broaden the base of support for his theory by connecting it with the increasing number of cognate studies that had begun appearing in the mid 1840s, studies now supplementing his and others' experimental findings and mathematical formulations with the kind of principled analysis of conceptual and theoretical issues that was contributing to an expanding appreciation of something like the conservation of energy in the late 1840s, even as much attention remained directed to the narrower but experimentally more tractable issue of the mechanical equivalent of heat. Before briefly reviewing a few notable experimental findings, Colding made a general appeal to experience: "It appears to

54. Colding 1847(1849), 239. On John Frederick William Herschel see Caneva 1993, 267.

me that experience has placed it beyond all doubt that the various forces of nature stand in a close and intimate connection with each other, insofar as experience shows that every force in the course of its action is able to produce [*fremkalde*, literally 'call forth'] other forces of nature and of freeing them into activity."[55] This experience included the production of heat, light, and fire via the vigorous rubbing of solids; the increase in body temperature following strong physical activity; and the electrification of rubbed amber. Experiments demonstrated further that enclosed volumes of steam and gases acquire, when heated, an increased elastic force (*Spændkraft*) capable of producing mechanical activity (i.e., a quantity of motion); that gases can be strongly heated by compression, in some cases giving rise to light and fire; that heat can be produced from the union (*Forening*) of opposing electricities; and that the union of chemical substances (or chemical forces) can produce both heat (even fire) and electrical currents (and thence also heat and light).

The profound implications of such examples of "this harmony among the forces of nature" had not gone unnoticed.[56] The earliest paper Colding knew of (from its translation in Poggendorff's *Annalen* in 1843) that developed this growing insight was Clapeyron's "On the motive force of heat," based on Carnot's axiom that, in Colding's words, "it is an absurdity to assume that one can produce motive force or heat from nothing."[57] Colding reviewed Clapeyron's theoretical derivation of Dulong's experimental findings on the thermal properties of gases and the experimental corroboration of one of Clapeyron's principal theoretical deductions by the Dutch physician and sometime experimentalist, Karel Willem Suerman.[58] As he had in his unpublished

55. Colding 1848(1850), 123 = Dahl 1972, 19.

56. Colding 1848(1850), 123 = Dahl 1972, 19: "det Dybere i denne Harmoni mellem Naturkræfterne."

57. Colding 1848(1850), 123 = Dahl 1972, 20. Cf. Clapeyron 1834(1843), 448: "seine [Carnot's] Beweise stützen sich auf die *Ungereimtheit, die es haben würde, anzunehmen, daß es möglich sey aus nichts bewegende Kraft oder Wärme zu erschaffen.*"

58. Alexander Karel Willem Suerman (1809–1840) earned a doctorate in medicine from the University of Utrecht in 1835 and received an honorary doctorate of philosophy there in 1836 with a dissertation on the specific heat of gases (Suerman 1836a; Thomas 1912). While he was in Paris (from August 1836 to February 1837) an abstract of that work appeared in French (Suerman 1836b, the "C.G." before his name presumably standing for Charles Guillaume), and later in German translation in Poggendorff's *Annalen* (Suerman 1836b[1837]), Colding's source. He provided experimental corroboration of a somewhat transformed expression of Clapeyron's theoretically derived formula, $\gamma = A - B \log p$, where γ is the specific heat at constant pressure p, A and B experimentally determined constants. Suerman referred to p. 170 of Clapeyron 1834 (= 1834[1843], 450 *bis*), where Clapeyron differentiated his basic formula for the absolute quantity of heat of a gas, $Q = R\,(B - C \log p)$, with respect to temperature t, holding p constant, to obtain an expression for specific heat at constant pressure: $R\,(dB/dt - dC/dt \log p)$, where B and C are functions of t—and hence of pv, since $pv = R(267 + t)$—and $R = p_o v_o/(267 + t_o)$. Suerman treated the A and B of his formula as constants since his experiments were done at uniform temperature. In Suerman's mind, he was less corroborating Clapeyron's formula than he was testing the

paper of 1845, Colding cited the long series of experiments Hess had reported in Poggendorff's *Annalen* between 1839 and 1842 on the heat produced by chemical reactions, experiments that demonstrated, in Colding's words, "that just as chemical substances enter into combinations with each other in which the quantities of the elements stand in a simple proportion to one another, so, too, quantities of heat are developed by the combinations of chemical substances that stand in entirely simple proportions to each other."[59] From these results Hess had enunciated the proposition, again in Colding's words, "[t]hat the quantity of heat that chemical substances can produce by their union is a definite amount determined by the substances that is independent of the time or the manner in which it takes place."[60]

Leaving unexpounded the implications of these findings for his doctrine of forces, Colding drew attention to the tenth of Liebig's *Chemical letters*, which compared the motive force of electromagnetism to that of steam and developed the idea that "chemical equivalents are certain invariable values for the effects produced [*Virkningsværdier*] that have reference to all the activities that they are capable of expressing."[61] (Liebig's *Wirkungswerthe* express the total effect a certain reaction can produce.) In a long footnote Colding quoted three paragraphs from Liebig's essay. Although Liebig declared that "[n]o force can arise out of nothing," his purpose was not to probe the nature of forces or their causal connections nor to oppose the possibility of perpetual motion, but to argue that it is much more advantageous to derive motive force through combustion in a steam engine than through electrochemical action.[62] Curiously, Colding did not quote the continuation of the passage, in which Liebig extended his analysis from chemical equivalents to heat, electricity, and magnetism:[63]

> Heat, electricity, and magnetism stand in a similar relationship to each other like the chemical equivalents of carbon, zinc, and oxygen. By means of a certain quantity of electricity we produce corresponding proportions of heat or

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accuracy of his own experiments; cf. Suerman 1836b(1837), 491. It may well have been Suerman who called Poggendorff's attention to Clapeyron's paper: "Dieser bisher nur von Wenigen (unter andern von *Suerman*; Annalen, Bd. XXXXI S. 491) beachtete Aufsatz schien seiner Wichtigkeit wegen noch jetzt ein volles Recht zur Aufnahme zu haben" (from Poggendorff's comments after the title to Clapeyron 1834(1843), 446).

59. Colding 1848(1850), 124 = Dahl 1972, 20.

60. Colding 1848(1850), 124 = Dahl 1972, 20–21.

61. Colding 1848(1850), 125 = Dahl 1972, 21, rendering Liebig's "gewisse unveränderliche...Wirkungswerthe..., die sich auf alle Thätigkeiten beziehen, welche sie zu äussern fähig sind," quoted in Colding's footnote from Liebig 1844, 114–115 (~ 1841, 2177, col. 1).

62. Liebig 1844, 117 (~ 1841, 2177, col. 2), quoted in Colding 1848(1850), 125 = Dahl 1972, 21.

63. Liebig 1844, 118 (~ 1841, 2177, col. 2).

> magnetic force that are mutually equivalent to each other. I purchase this electricity with chemical affinity, which, consumed in one form, produces heat, in another, electricity or magnetism. With a certain amount of affinity we produce an equivalent of electricity, just as vice versa by means of a certain quantity of electricity we bring about the decomposition of equivalents of chemical combinations.

Colding went on to quote at length from Moritz Hermann Jacobi's dismissive criticism of Liebig's employment of cause-and-effect reasoning to estimate the relative efficiency of variously powered electrochemical, magnetoelectric, and mechanical engines.[64] There followed an extensive (and silently edited) translation into Danish of a section in which Jacobi argued that the amount of work obtained from the electrolytic decomposition of a given amount of zinc in an electromagnetic machine is the same as the amount of work necessary for the galvanic dissolution of the same quantity of zinc by means of a magnetoelectric machine.

More directly germane to Colding's own enterprise was the train of reasoning that Michael Faraday had recently drawn from his ongoing "Experimental researches in electricity." As Faraday wrote (in a passage Colding translated into Danish from the German version of Poggendorff's *Annalen*):[65]

> I have long held an opinion, almost amounting to conviction, in common I believe with many other lovers of natural knowledge, that the various forms under which the forces of matter are made manifest have one common origin; or, in other words, are so directly related and mutually dependent, that they are convertible, as it were, one into another, and possess equivalents of power in their action [*und aequivalente Kräfte in ihren Wirkungen besitzen; og da virke som æqvivalente Kræfter*]. In modern times the proofs of their convertibility have been accumulated to a very considerable extent, and a commencement made of the determination of their equivalent forces.

As evidence for the extent to which "the idea of a higher point of unification [*Foreningspunkt*] and inner connection among the various forces of nature has seized the author [i.e., Faraday]," Colding noted that Faraday remained convinced that electricity must have an effect on light even though he had not been able to find experimental proof of the connection.[66]

Colding then devoted two pages to a discussion of "several works that have set themselves the task of determining the laws through which this intimate connection among the various forces of nature manifests itself."[67] These

64. Colding 1848(1850), 126 = Dahl 1972, 22, quoting from Jacobi 1846, 190–191.

65. Faraday 1845(1846a), 1–2 ~ 1845(1846b), 105–106, quoted in Danish in Colding 1848(1850), 127 = Dahl 1972, 23.

66. Colding 1848(1850), 127 = Dahl 1972, 23–24.

67. Colding 1848(1850), 127 = Dahl 1972, 24.

included Rumford's, Haldat's, and Becquerel's attempts to measure frictionally generated heat; various determinations of the heat evolved when a gas is compressed; and measurements, by Colladon and Sturm and by Ørsted, of the heat evolved when a liquid is compressed.

Toward the imperishability of forces

In language largely repeated from his still unpublished paper of 1847, Colding sketched the considerations that had first led him "to investigate the laws for the mutual dependence among forces:" d'Alembert's principle of lost forces; the progressive communication of activity from one material particle to another; and the absurdity of supposing that any "activity" or force might disappear as active causes.[68] He referred here, apparently for the first time, to the "imperishability" (*Uforgængelighed*) of forces: "It was the idea of forces' imperishability and their continual activity that provoked in me the desire to investigate the laws for the dependency of forces on each other, and it is with the feeling that this idea cannot possibly be incorrect that, already for nearly half a score of years, I have with intense delight sacrificed a large portion of my free time to contemplating and reflecting on the correctness of it."[69] After summarizing the experimental results he had reported in 1843, he recapped in self-quoted sentences the principal claims of his theory of forces, including its applicability to the question of proving the impossibility of a perpetuum mobile.[70] The rest of the paper described fourteen series of new experiments, which demonstrated in general "that the quantities of heat produced are proportional to the lost activities."[71] From his data he calculated a number "which indicates approximately the mechanical activity that is equivalent to the unit for quantities of heat. One thus finds:

$$(1\text{ lb. water})^{\text{heated 1 degree celsius}} = (1185.4\text{ lbs.})^{\text{raised 1 foot}}."^{72}$$

Ørsted's favorable report on Colding's paper, published in the Academy's *Oversigt* for 1848, contained the first appearance in print of Colding's experimental finding. In Ørsted's words, Colding had found "that the mechanical activity that is consumed [*medgaaer*] in order to produce by friction a unit of

68. Colding 1848(1850), 129 = Dahl 1972, 26. See the passages quoted above from Colding 1847(1849), 208–209, 215.

69. Colding 1848(1850), 130–131 = Dahl 1972, 27. See the passage quoted at note 39 from Colding 1845(MS), 1. Note that in Colding 1856, 143 (= Dahl 1972, 109) he used "uforgængelige" to gloss Mayer's "unzerstörliche," and although "imperishable" is the closer (and standard) translation of *uforgængelige*, its rendering as "indestructible" would also be warranted.

70. Most of these passages are quoted at notes 26, 27, and 34.

71. Colding 1848(1850), 143 = Dahl 1972, 42.

72. Colding 1848(1850), 146 = Dahl 1972, 43.

quantity of heat—the unit taken as 1 pound of water heated 1 degree Celsius—can be expressed by 1185 pounds raised 1 foot.''[73]

In a presentation to the Academy of Sciences the next year (1849) Colding summarized the general theoretical reflections that lay behind what he termed ''the principle for the lost activities that I previously proposed.''[74] He noted matter-of-factly that ''the various forces of nature, which are bound to the particles of matter,'' are responsible for the ceaseless development of the manifold bodies in nature and give bodies their characteristic and particular stamp.[75] The interaction (*Vexelvirkning*) of these forces brings about the ceaseless changes that constitute the distinctive feature of the material world (*det Materielle*). A consideration of ''nature's various activities'' must lead to the thought that ''these are produced and developed in order to disappear again after having produced one or another effect [*Virkning*] on the material particles;'' for it is well known that ''every activity—such as thermal activity, mechanical activity, electrical activity, etc.—has the capacity to produce [*frembringe*] all these forces'' and that when one produces quantities of mechanical work or heat by means of given quantities of mechanical work or heat, the latter activities disappear gradually as the new ones are produced.[76] It is, he said, a ''universally recognized truth'' that such production of heat or mechanical activity represents solely the communication of a given quantity of heat or mechanical activity from one system of material particles to another, and not its creation *de novo*.[77]

In contrast, the general relationship between active and produced forces has been misunderstood because of a tendency to think ''that the activities have fulfilled their role when certain material results have been produced.'' People have associated an active cause with a material effect and have thus failed to identify the corresponding active effect. For example, the mechanical activity contained in a quantity of falling water turns the waterwheel of a sawmill, whereby a certain ''material result'' is obtained—i.e., wood is sawed—''but the corresponding mechanical activity itself is [apparently] lost;'' similarly, the heat produced by the burning of coal in a steam engine sets a grist mill in motion, again producing a certain ''material result''—i.e., grain is ground—but that which produced this result has (so one thinks) disappeared, ''one says that is has become latent;'' thus, too, with the work performed by means of an electromagnetic machine powered by an electric

73. Ørsted 1848, 92–93.

74. Colding 1849(1850), 169 (''det tidligere af mig fremsatte Princip for de tabte Virksomheder'') = Dahl 1972, 47 = Colding 1849(1871), 1 (''the principle of the Lost Forces, which I formerly stated'').

75. Colding 1849(1850), 169 = Dahl 1972, 47 = Colding 1849(1871), 1.

76. Colding 1849(1850), 169 = Dahl 1972, 47–48 = Colding 1849(1871), 1–2.

77. Colding 1849(1850), 169–170 = Dahl 1972, 48 = Colding 1849(1871), 2.

current produced by chemical forces. "It is well known that, alongside the material work performed, there are developed new forces such as heat and electricity, but these are generally regarded as a matter of secondary importance [*som en Biting*]. But, such a way of looking at things always made him uneasy, and he was never able to accept it. As he had argued in earlier papers, the only natural thing was to conclude "[*t*]*hat forces can never disappear in the corporeal* [*world*], *and that it must consequently be a universal law of nature that forces without exception only undergo a change in form when they seem to disappear, and* [*that they*] *reappear thereafter as active causes with the same magnitude but in changed forms.*" To which he added in a footnote: "Compare on this connection: Die organische Bewegung in ihrem Zusammenhange mit dem Stoffwechsel by Dr. J. R. Mayer (Heilbronn 1845) and Helmholtz Ueber die Erhaltung der Kraft (Berlin 1847)"—his first (and unelaborated) reference to the work of these men.[78]

Having formulated his proposition (*Sætning*) in terms of forces (*Kræfter*), Colding explained (in a paragraph to be discussed later) why he had chosen to use the word activity (*Virksomhed*), a choice which yielded him the following reformulation of his fundamental proposition: "*That the different kinds of activity, such as thermal activity, mechanical activity, the activity produced by the interaction of chemical forces, etc., cannot be different in their essence, but that all the different kinds must be referable to one and the same activity, such as to the mechanical.*"[79] Colding's ontology of the physical world was thus, apparently, one entirely of matter in motion.

Colding ended this presentation of 1849, which would be his last on the subject until shortly before his election to the Academy of Sciences in 1856, with a recalculation of his value for "*the mechanical activity that is equal to the thermal activities in a unit of quantity of heat*" as 1204.3 foot-pounds.[80] Playing down the difference between this value and his earlier one as to be expected from the small number of experiments he had been able to do, he referred without elaboration to experiments by Joule.[81] It is noteworthy that

78. Colding 1849(1850), 170 = Dahl 1972, 48 = Colding 1849(1871), 2 (all quotes).

79. Colding 1849(1850), 171 = Dahl 1972, 49 = Colding 1849(1871), 2–3 (which generally rendered "Virksomhed" as "energy"). Ørsted called attention to the centrality of this implicitly reductionist ontology in his report to the Academy on Colding's paper: "Naturally he must assume that all forces have the same fundamental essence [*Grundvæsen*] and that heat must depend on an internal motion; likewise that the activity by means of which bodies are warm (conductive heat) depends on the oscillatory motions of the smallest particles, but radiant heat on oscillation in the aether, which Ampère has already assumed, and now after Melloni's investigations may well be the most accepted opinion" (1850b, 91).

80. Colding 1849(1850), 184 = Dahl 1972, 64 = Colding 1849(1871), 17 ("*the mechanical energy equivalent to the energy of heat in a unit quantity of heat*").

81. Colding 1849(1850), 185 = Dahl 1972, 64 = Colding 1849(1871), 17, referring to Joule 1847(1848).

Colding treated Joule as relevant to the experimental part of his work, Mayer and Helmholtz to the more conceptual-theoretical part, though in neither case did he go beyond a bare footnote mention. The distinction between those two quite different aspects of Colding's work remained a feature of his own expositions. Even as he was becoming aware of others' related work he remained largely within the expository boundaries he had set himself since the beginning.[82] These limits seem to have included publication only in Danish.

As of 1856 Colding's work seems to have been almost entirely unknown. The earliest reference found to it occurs in a widely reprinted lecture of 1854 in which Helmholtz mentioned that "Colding, a Dane, in 1843 submitted to the Copenhagen academy a paper that enunciated the same law [as Mayer] and also contained a few series of experiments toward its further establishment."[83] Helmholtz did not say how he learned of Colding's work.

The paper Colding submitted to the Academy on February 22, 1856, "Scientific reflections on the relationship between the spiritual life's activities and the universal forces of nature," went far beyond his previous accounts of his concept of force to reveal the metaphysical and theological considerations that lay behind his preoccupation with it.[84]

> In my earlier papers in the publications of the Academy of Sciences on the relationship among the universal forces of nature, I have developed the view that the forces of nature constitute not only that which is active in things [*det Virksomme ved Tingene*] but also that which is essential and exalted in them [*som er det Væsentlige og det Ophøiede ved disse*], that which gives substances their properties and characteristics and which is the cause of all the changes that take place ceaselessly in bodies. I have further endeavored to prove [*godtgjøre*] that the same forces that God from the first beginning placed in the world along with matter have later been continuously active and will continue to be so and to be equal to themselves in magnitude, activity, and abundance, without ever disappearing or ceasing to exist, and I have sought to prove this by demonstrating experimentally that the forces of nature are in their essence imperishable [*uforgængelige*]. It was my complete conviction that the forces of nature that now appear before us in both the organic and inorganic worlds, in the plant and animal kingdoms as well as in inanimate nature, not only have existed from the world's first beginning, but that these same forces have been continually active in developing the world toward the goal that was given at the creation itself.
>
> But nature's forces appeared to me to be not only that which is exalted

82. This remained true two years later when, in a paper on the motive power of steam in steam engines, Colding cited Clausius' important paper of 1850; see Colding 1851(1852), 6 and 28 = Dahl 1972, 72 and 97.

83. Helmholtz 1854 (1896), 62–63 ~ 1854(1856), 499. Helmholtz ignored Colding's papers in his reviews of the literature for the *Fortschritte der Physik* published between 1847 and 1859, nor did others' reviews there mention Colding's work.

84. Colding 1856, 136–137 = Dahl 1972, 105–106.

> above the corporeal world, I had much more the complete conviction that these forces must be related not only to the human spirit [*Aand*], but to eternal reason [*Fornuft*] itself, and I must admit that it was this feeling that led me to the idea of the imperishability of forces; for if the forces of nature are entities [*Störrelser*] related to that which is spiritual in the world [*det Aandelige i Tilværelsen*], to the reason that pervades nature and that in human beings has come to self-consciousness and to the recognition of the rational [*det Fornuftige*] in nature, so it was also clear to me that if there is truth in the feeling we have within us that the human spirit in its own essence bears witness to its immortality, so must there also be truth in the idea that the forces of nature themselves are exalted above perishability. These grounds for the autonomy [*Selvstændighed*] and imperishability of forces were completely convincing for me; but as long as only I had them, I did not dare set forth my thoughts; for I knew very well that the entire question of the existence of the spiritual had been doubted and opposed by many who could defend their opinion on purely rational grounds much better than I. I therefore set myself the task of showing by scientific means whether I was right or wrong in my assertion; for the matter had never been investigated in this manner, and here we must surely have the means of obtaining an incontrovertible proof for or against the imperishability of forces.

When Colding looked at well-known phenomena he noticed that wherever we see *Virksamheden* disappear in the performance of the work "for which the forces are employed," we see new forces appear *as if* from nothing, in clear accord with his notion "that there actually exists in nature only a single fundamental force [*en eneste Grundkraft*] that can assume all the different forms in which we recognize the forces of nature."[85] His task was then to demonstrate experimentally that when work is performed the amount of heat produced is proportional to the quantity of work (*Arbeidsmængde*) lost and that that heat in turn can produce the same amount of work that was previously lost; and so on with other combinations of forces. Although his own experiments had not gone beyond demonstrating that the heat produced by the friction of different kinds of bodies is always proportional to the lost quantities of work and is independent of other circumstances, he did not doubt the universal correctness of his principle of the imperishability of forces.

It was, he said, several years after 1843 that he first learned of others' work in the same area, in particular of Mayer's and Joule's. Colding was concerned to defend his priority rights against Mayer as "discoverer of this law of nature," noting Mayer's own claims in this regard in the *Comptes rendus* of 1848, in which Mayer recalled his first publication in 1842 in Wöhler and Liebig's *Annalen* and his later more general treatment in a work of 1845.[86] Colding criticized Mayer's paper of 1842 for being wholly

85. Colding 1856, 137, 138 = Dahl 1972, 106. This passage is quoted in full at note 142.

86. Colding 1856, 140–141, on 140 = Dahl 1972, 108. It is not clear just how or when Colding learned of Mayer's and Joule's work.

theoretical and hence without real—i.e., experimental—proof of his theory of forces. Mayer had stated without derivation his value for the quantitative equivalence between the fall of a weight and the heating of a mass of water, obscuring the fact that he had found experimental corroboration for at least part of his theory from data on the compression and thermal expansion of gases. Colding quibbled with Mayer's schematic yet clear and workable symbolic formula showing that when hydrogen and oxygen combine to form water *and heat*, the equation has to be balanced by indicating the presence of some (chemical) force on the side of the reactants. He paraphrased Mayer's argument that, since a force as a cause must have a force as an effect, a cause that raises a weight is a force, as must then be the raised weight itself. Mayer had concluded from this that "spatial difference of ponderable objects is a force," for which he introduced the term *Fallkraft* as distinct from the actual falling of the raised body.[87] Colding rejected this reasoning: he appears not to have agreed with Mayer that a weight resting on the ground is not a bona fide force.

Colding curiously misread Mayer as saying that "the only forces he will consider are what we call living forces [*levende Kræfter*]."[88] His understanding of the term "force" was still implicitly attached to its traditional application to attractive and repulsive forces regarded as constituting the fundamental properties of bodies; consequently he rejected Mayer's denial of any equation between a force and a property (*Egenskab, Eigenschaft*) of matter.[89] For Colding, chemical properties are forces. Mayer had argued that we often see motion disappear without passing over into other motion and without raising a weight, but since a force once present cannot just disappear, we conclude that the force has assumed another form, namely heat. But Colding could not conceive that the living force that propagates itself from particle to particle of matter could ever cease to exist; that is, his attachment to the mode-of-motion conception of heat was so basic and unquestioned that he could not appreciate Mayer's antireductionist and implicitly phenomenological equation between motion and heat.[90] Colding offered the following summary estimation of the relative merits of Mayer's paper of 1842 and his own of 1843 (published first in 1856, a fact Colding neglected to mention):[91]

87. Colding 1856, 145 = Dahl 1972, 111; cf. Mayer 1842, 235.

88. Colding 1856, 145 = Dahl 1972, 111.

89. Colding 1856, 145 = Dahl 1972, 111: "He [Mayer] says: between a property and a force there cannot be established any well-grounded equation [*Ligning*]; for a property is something entirely different from a force, whose chief properties are 'Unzerstörlichkeit und Wandelbarkeit,' and Dr. *Mayer* thus denies that chemical properties are forces, which is once again demonstrably a false conclusion."

90. On Mayer's conception of heat see Caneva 1993, 24–25, 28–29, 192.

91. Colding 1856, 147–148 (correcting the text's "Opfattelsesmaads") = Dahl 1972, 112–113.

> Whereas Dr. *Mayer*, in developing his ideas, has proceeded from an incorrect view of the loss of living forces [and] of the development of heat through chemical combinations, as well as from an incorrect conception of the relation between the properties of bodies and the forces of nature, and has only sought to demonstrate the correctness of the actual idea that elicited his remarks by means of the rational conclusions that I have especially emphasized in the foregoing, and on the other hand has not even compared these ideas with the definite results of *Rumford, Haldet* [sic], *Dulong*, or others that already existed, much less had he himself carried out experiments that rendered probable the correctness of his fundamental idea, but instead contented himself with referring to extremely rough facts on the relationship between heat and motive force—I, in my first paper, have not only set forth the correct reason that a living force must assume the form of heat, but I have in general, as I believe, clearly and distinctly shown the necessity [of the proposition] that all forces of nature must in their essence be imperishable and in form be changeable [*foranderlige*]. But I did not content myself with that, I pointed out in addition that this law is corroborated by nature via all the previously performed experiments, namely by *Rumford's, Haldet's, Dulong's,* and *Ørsted's* experiments on the development of heat with solid, liquid, and aeriform bodies; moreover I myself had constructed a larger apparatus in order to demonstrate experimentally the correctness of my ideas and with it I carried out all the experiments reported in my paper on the heat developed by the friction of different bodies, whereby it was established that my way of conceiving things [*mit Opfattelsesmaade*] was confirmed by nature, and only after that did I announce what I had found.

Having thus defended his claim to priority with regard to the experimental demonstration of "the imperishability of the forces of nature," Colding began a brief account of other relevant work with a summary of Joule's several experimental determinations of the mechanical value of heat. Accepting the greater accuracy of Joule's measurements while rejecting Joule's rationale for their comparative weighting, Colding recognized Joule's success in extending the experimental demonstration of the equivalence of work and heat to more complex systems involving magnetoelectricity, electromagnetism, and chemical activity. To his citation in earlier papers of Hess' thermochemical experiments he now added those of his countryman, Julius Thomsen (1826–1909), who had, furthermore, begun to subject chemical reactions to mathematical calculation. He cited his own paper of 1851 on steam engines for evidence of how his principle both received corroboration from, and shed light on, their operation; and he used Regnault's redetermination of the specific heat of air to redo his calculation of 1849 that one unit of heat (*Varme-Eenhed*) is equal to 1204.3 units of work (*Arbeids-Eenheder*). His new number, 1352.2, was essentially identical to the 1352 he calculated from his weighted averaging of Joule's experimental findings: "[T]here can therefore be no doubt that this is the correct numerical equivalent [*AEqvivalenttal*] for heat and mechanical activity."[92] With this Colding concluded the first section of his paper: "If we

92. Colding 1856, 155 = Dahl 1972, 118.

now summarize all of this succinctly, then I believe that we already have the most incontrovertible proofs that the fundamental proposition concerning the imperishability of forces is one of the great universal laws in nature; and with that we have, then, also proven that the imperishability of forces is a principle pervading all of nature that has been given from the first beginning and will continue to exist for all time."[93]

The wider dissemination of Colding's work

Thus as of 1856 Colding's work lay little read and known if at all through infrequent unelaborated references.[94] Emile Verdet's technical and historical exposition of the mechanical theory of heat in 1862 mentioned Colding's presentation to the Academy of Sciences in Copenhagen of several papers that contained ideas similar to Mayer's and an experimental determination of the mechanical equivalent of heat by friction, but (he added) they were published in Danish several years after their presentation and had exerted scarcely any influence on the development of the science.[95] John Tyndall's brief reference to Colding (via Helmholtz' address of 1854 and Verdet's sketch) in the May 1863 issue of the *Philosophical magazine,* followed the next month by the publication there of an extract of Verdet's work containing his mention of Colding, prompted him in November 1863 to submit to the editors his own contribution to the ongoing controversy over the discovery of what was then increasingly termed the conservation of energy.[96]

Colding reported that, since no library in Copenhagen carried the *Philosophical magazine*, he had derived his knowledge of its contents principally from Poggendorff's *Annalen* until subscribing to it himself in January of 1863. The title given to the English translation of Colding's Danish essay was "On the history of the principle of the conservation of energy," though Colding himself spoke of "the new principle in relation to the forces of nature, which in Danish is called 'The principle of the imperishableness or perpetuity of Energy' (*Principet for Kræfternes Uforgængelighed*), the most important part of which is the Mechanical Theory of Heat."[97] His essay contained an

93. Colding 1856, 155 = Dahl 1972, 118.

94. Hermann von Kauffmann (1817–1858), a Danish artillery officer who wrote a little-noted but solid booklet entitled *Die Arbeit der Wärme* (1848)—published, to be sure, the year before the appearance in print of any of Colding's papers—appears not to have known of Colding's work, nor was he cited in Julius Thomsen's impressive thermochemical papers (e.g., Thomsen 1853).

95. Verdet 1862, 115–117 ~ 1868–72, *7* (1868), xcvi–xcvii ~ 1862(1863), 471–472.

96. Tyndall 1863, 372, 373; Verdet 1862(1863), 471–472; Colding 1863(1864a). For a bibliography of this interchange see Blüh 1952, 220.

97. Colding 1863(1864a), 57 = Dahl 1972, 159; Verdet's translation rendered this passage as "principe de l'indestructibilité ou de la conservation de l'énergie;" Colding 1863(1864b), 466.

historical accounting of the general considerations that led him to formulate his principle of forces, a sketch of his first paper of 1843 with the experimental findings reported there, and an elaboration of the cosmological and theological speculations developed in his paper of 1856. He only just hinted at the kind of mathematical treatment he had given his theory and it would have been easy to miss the depth and seriousness of his work. Thus the more technical aspects of Colding's work lay largely unseen until 1871, when Peter Guthrie Tait arranged for the publication of Colding's paper of 1849.[98]

On May 21, 1864 Colding received the issue of the *Comptes rendus* for the preceding December 28, in which he read the announcement of the Paris Academy's Prix Bordin of 3,000 francs for "a work bringing *a notable improvement to the mechanical theory of heat.*" Entries were due by the first of July.[99] Colding cobbled together a paper consisting of twenty-two edited pages from his paper of 1851 on steam engines embedded within forty-five double pages of manuscript copy.[100] His prime expository goal was to identify the fundamental principle of the mechanical theory of heat—"that everywhere in nature there exists a constant proportion between the quantity of activity we call *a unit of heat* and the quantity of activity we call *a unit of work*" such that these quantities of activity "can completely stand in for and replace each other as equivalent forces"—not only as "a fundamental law for all of nature" but as a special case of a more general law of nature.[101] To do that, however, one must first obtain "a clear and complete knowledge" of the forces of nature—of "that which is most sublime in nature"—which make nature what it is and on which its further development depends.[102]

Colding argued that "the first shortcoming that attaches to the customary mechanical theory of heat"—"which, as the name indicates, treats of the

98. See the undated note appended by Colding's son, Torben Andreas Colding (1849–1933), to one of the manuscripts of Colding's Prix Bordin entry (Colding 1846b(MS), as printed in Dahl 1972, 157): "On the occasion of his nomination for an Honorary Doctorate at the University of Edinburgh in 1871 he delivered this paper [i.e., Colding 1849(1850)], as well as the aforementioned manuscript [i.e., Colding 1846b(MS)], to P.G. Tait, Professor in Physics at the University of Edinburgh, who arranged for a translation of the 1850 paper in the *Philosophical Magazine* for July, 1871, where the basic formulae may therefore be found." A note by Colding on the title page of Colding 1864a(MS) says that he sent the manuscript to Tait during the summer of 1871 and got it back in Feb 1886.

99. Colding 1864a(MS), 1; Dahl 1972, 154 (which quotes the wording of the prize).

100. Colding 1864a(MS) incorporates pp. 3–6 and 15–32 of Colding 1851(1852).

101. Colding 1864a(MS), 1: "at der overalt i Naturen findes et constant Forhold Sted imellem den Virksamhedsmængde, som vi kalde *en Varme-Eenhed* og den Virksamhedsmængde, vi kalde *en Arbeids-Eenhed;*" "fuldstændigt kunne træde istedetfor og erstatte hinanden som æqvivalente Kræfter;" "en Grundlov for hele Naturen." Cf. Dahl 1972, 129. See also Colding 1864a(MS), 4 *bzw*. Dahl 1972, 131.

102. Colding 1864a(MS), 2: "en klar og fuldkommen Kundskab;" "det Ypperste i Naturen." Cf. Dahl 1972, 130.

relationship of the mechanical force (or more correctly the mechanical activity) to heat"—is that it can only be applied to the relationship between heat and mechanical force, and not also to any of the other various forces of nature.[103] "The real fundamental principle" is *not* "that for all of nature's forces there exist definite proportions in which they act as equivalent forces."[104] Recalling his conviction that "forces must be regarded as that which is active and most sublime in nature, [as] that which gives nature its life, its reality, and its worth," and "as that which is most exalted in nature," Colding argued that our inability to know what forces are in their essence is due to the fact "that forces are of a spiritual nature, whereas we are only human beings."[105] If forces are spiritual, then their undoubted existence provides us with infallible proof of the existence of the spiritual (*det Aandeliges Existens*) in nature, and if it is also the case—as we believe—that the spiritual is immortal (*at det Aandelige er udødeligt*), then it must also be a law of nature "[t]hat forces are in their essence imperishable. This [he added] is the fundamental proposition upon which my theory rests."[106] A force may transform itself (*omdanne sig*) in various ways, but it can never perish (*forgaaer*). In accordance with this "principle of the imperishability of the forces of nature" it is impossible that a given mechanical force can be annihilated (*tilintetgjort*), from which we conclude "that the lost mechanical force or the lost mechanical activity does not merely call forth the newly appearing forces, but that it is the lost forces themselves that appear in their original magnitude in the new forms of force—such as electricity, heat, etc.—such that the sum of all the quantities of activity is the same before and after the change in form."[107] That sum has been raised above all perishability by the Creator.[108]

103. Colding 1864a(MS), 4: "den fórste Ufuldkommenhed, der klæber ved den sædvanlige mechaniske Varmet-Theori;" "der, som Navnet antyder, behandler den mechaniske Krafts eller rettere den mechaniske Virksomheds Forhold til Varmen." Cf. Dahl 1972, 131.

104. Colding 1864a(MS), 5: "Det egentlige Grundprincip;" "at der for alle Naturens Kræfter existerer bestemte Forhold, hvori de virke som æqvivalente Kræfter." Cf. Dahl 1972, 131 and Marstrand 1929, 49.

105. Colding 1864a(MS), 5: "Kræfterne maa anses som det Ypperste og det Virksomme i Naturen, det som giver Naturen sit Liv, sin Virkelighed og sit Værd;" "ogsaa det mest Ophójede i Naturen;" "at Kræfterne ere af aandelige Natur, imedens vi kun ere Mennesker." Cf. Dahl 1972, 131–132 and Marstrand 1929, 50.

106. Colding 1864a(MS), 5–6: "At Naturkræfterne i deres Væsen ere uforgængelige. Dette er den Grundsætning, hvorpaa min Theori hviler." Cf. Dahl 1972, 132 and Marstrand 1929, 50.

107. Colding 1864a(MS), 7: "*Princip for Naturkræfternes Uforgjængelighed*;" "at den tabte mechaniske Kraft eller tabte mechaniske Virksomhed fremkalder ikke blot de nye fremtrædende Kræfter, men at det er de tabte Kræfter selv, som i deres oprindelige Magtfylde fremtræde in de nye Kraftformer, saasom Electricitet, Varme o.s.v., saaledes at Summen af alle Virksomhedsmængderne er den samme fór og efter Formforandringen." Cf. Dahl 1972, 132.

108. Colding 1864a(MS), 8: "thi Summen af alle Virksomhedsmængderne er constant. Den er af Skaberen hævt over al Forgjængelighed." Cf. Dahl 1972, 133.

Notwithstanding the title given to the English translation of Colding's paper, he himself never used the language of conservation—as did others, and as might have been available to him, a student of mechanics, by way of analogy with the principle of conservation of *vis viva* ("Principet for Vedligeholdelsen af den levende Kraft")—let alone formulate a unified general concept of energy under any name.[109] Colding always spoke of the "forces" of nature, virtually never of "force" as an abstract general concept: the only exception that has come to light is one entirely atypical assertion "that there actually exists in nature only a single fundamental force that can assume all the different forms in which we recognize the forces of nature."[110] Although his concept of activity (*Virksomhed*) functioned in a way closer to the meaning of energy, in the end the centerpiece of his theory remained the principle of the imperishability of the forces of nature, under which he subsumed as a special case amenable to experimental determination the quantitative equivalence between heat and work (or mechanical activity, as he more often termed it).

2. COLDING'S PATH: THE CONCEPTUAL FIELDS OF FORCES AND ACTIVITIES

Toward a recapturing of Colding's forces

One of the pitfalls bedeviling the study of past science is the danger of reading current meanings back into older usages, of failing to grasp the sense of words in their own context or even to notice significant patterns. Thus no one who has treated Colding as one of the so-called co-discoverers of conservation of energy appears to have noticed that he had no explicitly formulated generalized *concept* of energy, under any term. Only by determining the meanings for Colding of such cardinal terms as force and activity can one hope to have even a roughly faithful notion of what he thought he was claiming and of how his work related to that of his contemporaries. We have seen in a general way Colding's terminological wavering between "force" and "activity" even as he continued to state his fundamental principle in terms of "the imperishability of the forces of nature"—never, be it noted, of the imperishability of *force*. The only place he explicitly discussed his terminology was in a paragraph of his paper of 1849 omitted (as Dahl noted) from the English translation published 1871. After having used both terms without clear distinction, he wrote:[111]

109. For the Danish phrase see Ramus 1852, 221.
110. Quoted at note 85.
111. Colding 1849(1850), 170–171 = Dahl 1972, 48–49; cf. Dahl 1972, 180, n. 102.

> I have here, as previously, used the expression "activity" because it seems to me, according to the meaning of the word, clearly to indicate that it is a question of the forces that are present in, and constitute the essence of, any motion of a number of material particles. With the word "activity" I will thus denote in general the totality [*det hele Indbegreb*] of motion, or in other words the totality of life [*det hele Liv*] which the originally present cause of motion has produced [*fremkaldt*] among the material particles and which is therefore identical to [*Et med*] the cause itself. The expression "the lost activity" must consequently not be confused with that which in d'Alembert's principle is denoted by the lost forces; for in d'Alembert's principle it is only a question of an equilibrium among the manifestations of force such that these can produce [*frembringe*] no further effects, but not of an annihilation of an already present activity, this word taken in the above indicated meaning.

This is as close as Colding ever got to an explicit definition of his key terms. With something less than complete clarity or consistency, he seems here to be using the word force to refer to the underlying causes of motion of the particles of matter and activity to refer to the motions themselves; what he further meant by the totality of life remains obscure. With this understanding we can begin to tease out a pattern of meanings from Colding's words.

Although Colding sometimes repeated the then-common line that we cannot know the essence of forces, only their effects, he did not hesitate to pronounce that "the forces of nature are in their essence imperishable."[112] Furthermore, his attachment to an ontology of matter-in-motion was so taken for granted that he could speak without apparent self-consciousness of "the inner activity that constitutes the essence of the produced activity—whether it is heat, electricity, etc."[113] Although Colding never formalized a complete list of the things he regarded as forces—usually he named one or two followed by "etc."—one can extract from his papers a reasonably coherent set: motive force (the pushes and pulls that create or destroy motion), heat, electricity, chemical forces, and (less often) magnetism, with the rare addition of light, fire, and elastic force. Alas, he also regularly spoke of mechanical, thermal, electrical, and chemical *activity,* and we will have to probe further for a distinction. As noted earlier, Colding rejected Mayer's denial that a weight lying on the ground is a bona fide force, and, despite his education in mechanics,

112. See the passage quoted at note 84 (quote). To the examples cited at notes 24 and 105 concerning essence, cf. Colding 1864a(MS), 5 (corresponding to Dahl 1972, 131 and Marstrand 1929, 50): "It is remarkable that nature's forces in their internal essence as well are that which is most incomprehensible in nature, but they afford infallible testimony to their existence, grandeur, and power through their powerful effects, which confront us daily." ("Mærkeligt er det, at Naturens Kræfter tillige i deres indre Væsen ere det mest ubegribelige i Naturen, men de afgive et ufeilbarligt Vidnesbyrde om deres Existens, Storhed og Mægtighed gjennem deres mægtige Virkninger, som dagligt træde os imóde.")

113. See the passages quoted at notes 24, 41 (quote), and 79.

nowhere did he appear to recognize the need to define something like Mayer's fallforce—our gravitational potential energy—nor did he appear to recognize the analogously problematic status of his elastic force. Aside from a reference to "the universal attraction that holds all the heavenly bodies in their places," which is somehow also the cause of the sun's heat and light, he never significantly discussed gravitation or the force of gravity in his more properly scientific papers. What he did say in that regard in his most wide-ranging speculative outing will be examined below.[114]

As also noted earlier, Colding *rejected* Mayer's insistence that forces must be distinguished from the properties of things. For him the forces of nature are "bound to the particles of matter"; they are "that which is active in things," the causes of change in the material world, and "that which gives substances their properties and characteristics."[115] Thus chemical properties are forces in Colding's sense of the term. At least that is what he sometimes said. Elsewhere he took it as proven "that that which physicists call the forces of nature are [*sic*] not the properties of bodies but, on the contrary, is that which gives bodies and substances their properties and which, [when] separated from them, makes bodies different from what they were earlier. The forces themselves, their essence and nature, are assuredly completely incomprehensible to us, and we can only approximately conceive what they are by seeing their effects."[116] It is clear, he asserted, "that forces exist, that they are autonomous entities [*selvstændige Størrelser*] that persist when the bodies change."[117] Since several of these mutually inconsistent passages come from the same paper, we are dealing here not simply with a change of views over time, although that may have played a role. More significant seems to have been Colding's desire, in his more speculatively unrestrained moments, to identify essential continuities between physical forces and the free human spirit.

Whatever differences there were in the meanings Colding assigned to forces and activities, terminologically the two overlapped considerably: electricity, heat, "etc." are now forces, now activities, and both can be qualified as "lost."[118] Yet the terms were not universally interchangeable. As illustrated abundantly (if tacitly) in passages already cited, forces, not activities, are termed imperishable; forces, not activities, change form; forces are active,

114. See the passage quoted at note 54.

115. See the passages quoted at notes 75 and 84.

116. Colding 1856, 158 = Dahl 1972, 120. Cf. ibid., 143 (*bzw.* 110): "The idea of forces' independence from bodies and their autonomous nature [*Væsen*] stood from the beginning also for me [as for Mayer] as an exceedingly attractive and natural idea."

117. Colding 1856, 158 = Dahl 1972, 120.

118. With respect to the terminology of force and activity, see the passages quoted at notes, 25, 39, 41, 43, 47, 50, 51, 74, 76, 78, 84, and 101; with respect to their qualification as lost, see the passages quoted at notes, 25, 27, 31, 33, 34, 41, 49, 50, 51, 74, and 107.

have activity, and call forth other forces (though occasionally it is the activities that produce the forces). The elastic force, for example, is capable of producing mechanical activity. Contrariwise, activities, not forces, represent work done. Colding spoke of quantities of activity, work, and heat, of units of activity, work, and heat, not of quantities or units of force.[119] When he wrote that he used the word activity to "denote in general the totality of motion...which the originally present cause of motion has produced," we perhaps glimpse a rough conception of activity as an integral of the force, especially since in contemporary usage forces were regularly identified as causes of motion.[120]

When he wrote more precisely that "the lost activity's increase is equal to the lost force, multiplied by the length of the path traversed in that moment," and when he corrected himself in referring to "the relationship of the mechanical force (or more correctly the mechanical activity) to heat," it would seem that at least by 1864 he had come to use force and activity in ways analogous to the modern understanding of force and work.[121] Nevertheless, Colding never propounded a theory that defined something like energy with either conceptual or terminological clarity, despite his conviction that the quantity of work-producing activity in the world does not change when its form changes. The forces whose imperishability lay at the heart of his thinking were not, for the most part, equivalent to quantities we would call energy. These facts have been obscured not only by the obscurity of Colding's prose, but by an abiding confusion, then as now, over the relationship between a general theory of the conservation of energy and a more limited statement of the quantitative equivalence between heat and motion.[122] The spheres of relevance within which those two principles were variously understood and defended were very different.

According to passages quoted earlier from papers of 1856 and 1864, Colding was initially led to contemplate the imperishability of forces from his understanding of forces as related to the spiritual in nature (*det Aandelige*), to the human spirit, and to eternal, divine reason: since Colding firmly accepted

119. To the many already cited examples of Colding's usage, add Colding 1864a(MS), 6: "the forces that are employed in order to carry out what we call work are consumed and disappear in the course of the work" ("de Kræfter som anvendes paa at udfóre hvad vi kalde et Arbeide, forbruges og forsvinde under Arbeidet"). Cf. Dahl 1972, 132.

120. See the passage quoted at note 111. On forces as causes see Caneva 1993, 161–164.

121. See the passages quoted at notes 50 and 103.

122. Carl Holtzmann (1811–1865) nicely illustrates the conceptual distance between the two. Although his 1845 booklet and its 1848 summary in Poggendorff's *Annalen* are regularly and correctly cited for his determination of the mechanical value of heat, his 1861 textbook on theoretical mechanics devoted five pages to "the theorem of work, or the principle of living forces" (pp. 269–273) but said nothing about the conservation of energy, long after that idea had achieved widespread currency.

the imperishability of the human spirit it then followed that forces, too, must be imperishable. Forces, he asserted, are that which is exalted and most sublime in nature (*det Ophøiede* and *det Ypperste*).[123] Colding opened the metaphysical section of his paper of 1856 with a concise recapitulation of his train of thinking:[124]

> My first thought that the forces of nature must be imperishable I derived...from the view that the forces in nature must be related to that which is spiritual in nature, to the eternal reason as well as to the human spirit. It was thus the religious conception of life that led me to the thought of the imperishability of the forces of nature. It was by this means that I became convinced that, as certainly as it is true that the human spirit is immortal, so must it certainly also be a universal law of nature that the forces of nature are imperishable.

From passages already cited we know that it was the idea of the imperishability and continuous activity of forces that then aroused in him "the desire to investigate the laws for the dependency of forces on each other," whereby he arrived at his "first fundamental idea, that the forces are the same only appearing under changed forms."[125] Although Colding in fact waffled with respect to the independence of forces from matter, he claimed that he was early convinced that they are indeed autonomous entities, independent of matter.[126]

D'Alembert's lost forces

Colding arrived at the conclusion that "the forces are the same only appearing under changed forms" by reflecting on troubling implications of what he termed d'Alembert's principle of lost forces.[127] D'Alembert himself enunciated no such explicit principle, though he did speak not only of forces that mutually destroy each other (once, of a force that destroys itself) and of forces that hold each other in equilibrium, but also of "the forces lost" in a given system of bodies in interaction and of "the force lost by each particle," though without using the words *force perdue* by themselves as any kind of

123. See the passages quoted at notes 84, 105, and 106.

124. Colding 1856, 155 = Dahl 1972, 118; quoted in Dahl 1963, 183, 1972, xxxii, and 1978, 85. Cf. Colding 1863(1864a), 57–58 = Dahl 1972, 160. Dowd (1995) treated Colding—along with Mayer and (to a lesser extent) Joule—as examples of "religion informing science."

125. See the passages quoted at notes 69 and 47, resp.

126. See the passage quoted in note 117.

127. See the passages cited at notes 42 and 111. Elsewhere Colding wrote that "[t]he first guiding idea [with regard to the mutual dependence among forces] I grasped while contemplating the well-known 'd'Alembert's principle concerning lost forces'" (Colding 1848[1850], 129 = Dahl 1972, 26). Cf. Colding 1863(1864a), 58 = Dahl 1972, 160. Dahl (1972, xviii–xix and 170, n. 32) did not know what to make of Colding's claim.

special technical term.[128] The issue for d'Alembert was to distinguish between the forces (or, as he called them, *mouvemens* and *impulsions*) active among a system of particles that contribute to their motion from the forces that cancel each other out.[129] That was also the way Lagrange interpreted what he referred to in 1811 as "the principle that d'Alembert has given in his *Treatise on dynamics*": "If one impresses onto several bodies motions [*mouvemens*] that they are forced to change as a result of their mutual action, it is clear that one can regard these motions as composed of those that the bodies will actually acquire and of other motions that are destroyed; from which it follows that these latter must be such that the bodies animated by only these motions are in equilibrium."[130] He did not speak of lost forces.

In the discussion of d'Alembert's principle in the first edition (1811) of his *Treatise on mechanics,* Poisson spoke of "the velocities that will be lost or gained" by the interacting material points and concluded that "*there will be equilibrium in the system between the quantities of motion* [i.e., momenta] *lost or gained*...because if these forces were not in equilibrium" the masses would not have the velocities they do have. His language blurred the issue of whether d'Alembert's principle refers to velocities, momenta, or forces, and whether it is quantities of motion or forces that are lost.[131] Considering later the collision between two bodies of arbitrary shape, Poisson referred to the equilibrium that exists "between the quantities of motion lost or gained" by the bodies' molecules and concluded that "[t]he quantities of motion that the collision causes all of the molecules of each of the two bodies to lose or gain will thus have a unique resultant, directed along the normal, at the point of contact μ; the magnitude of this force will be the same for the two bodies, and it will be, for each body, equal and opposite to the *percussion* that it experiences."[132] Coriolis's treatment of d'Alembert's principle in 1829 likewise moved back and forth between quantities of motion and forces as he, too, spoke regularly of "the quantities of motion lost or gained" in the collision of several bodies.[133]

Perhaps the first formal and explicit use of the term "lost force" occurred in the second edition (1833) of Poisson's *Treatise on mechanics*, a work Colding knew.[134] Poisson noted that the principle he later referred to as

128. D'Alembert 1743, 51, 53–54, 151; 1758, 73–75, 226; quotes on 135 and 137 *bzw.* 207 and 208. Although the relevant parts of the two editions are largely the same, in 1758 he spoke four more times of the "force lost" in certain circumstances (199–200).

129. D'Alembert 1743, 50–51.

130. Lagrange 1811–15, *1* (1811), 239.

131. Poisson 1811, *2*, 42–43, on 43.

132. Poisson 1811, *2*, 220, 221.

133. Coriolis 1829, 120–125, on 123; cf. 125.

134. He referred to "Poisson's Mechanik §566" in Colding 1851(1852), 13 = Dahl 1972, 80, the subject of which corresponds better to the second than to the first edition. A German translation of this second edition appeared in 1835–36.

"d'Alembert's principle" can be used to solve for the velocities of a system of material points subjected to given forces and constraints:[135]

> In order to enunciate this principle in a precise manner, let m be the mass of one of the material points under consideration, and $u\tau$ the velocity that the force that acts upon it would impress upon it, if it were free, in the infinitely small time τ. Let us call $q\tau$ the increase in velocity that will likewise take place during this same instant and whose direction will, in general, differ from that of the given velocity $u\tau$. By means of the rule of the parallelogram of forces, which applies equally to velocities (n° 145), let us decompose $u\tau$ into two other velocities, of which one be $q\tau$, and the other will be represented by $p\tau$. The motive force applied to the moving body [*mobile*] will be measured by the product mu; those which will be capable of [producing] velocities $q\tau$ and $p\tau$ will have the values mq and mp; and we will be able to regard the given force mu as the resultant of the force mq, to which is due the increase in velocity that actually takes place, and the force mp, whose effect is destroyed by the connections among the points of the system. We shall call this last the *lost force*.

Thus the lost forces effectively hold each other in equilibrium and, as Poisson noted, this is true not only for the lost forces but also for the *quantités de mouvement* lost.[136]

Norwegian astronomer Christopher Hansteen (1784–1873) basically followed Poisson's lead in 1838 in his Danish-language *Textbook on mechanics*. In a system of particles subjected to various forces and constraints, a certain component of force for each particle "must become lost on account of the connection between the masses, since these forces have no influence on the motion. *These lost forces must therefore hold each other in equilibrium.*"[137] Significantly, the usage closest to Colding's is that of his professor of mechanics, Christian Ramus, who not only followed Poisson and Hansteen in his presentation of "d'Alembert's principle" by introducing the concept of lost force and noting that "the whole system of lost forces is in equilibrium," but who—alone among the writers I have been able to identify—also spoke of "*d'Alembert's* principle for the equilibrium of the lost forces [d'Alembert's *Princip for de tabte Kræfters Ligevægt*]."[138] Colding's more

135. Poisson 1833, 2, 2; cf. 3 and 6 for "le principe de D'Alembert."

136. Poisson 1833, 2, 3, 6–7, 256–257, 393.

137. Hansteen 1836–38, 2, pt. 2 (1838), 568: "maa gaae tabt formedelst Massernes Forbindelse, siden disse Kræfter ingen Inflydelse have paa Bevægelsen. *Disse tabte Kræfter maa altsaa holde hinanden i Ligevægt.*" Martin Ohm (1836–38, *3* [1838], 25–26) likewise interpreted "D'Alembert's Lehrsatz" in terms of forces, including the lost forces—the term occurred here in the singular, "die *verlorne Kraft*"—which "sich gegenseitig...aufheben und vernichten."

138. Ramus 1852, 208 and 209, first and last two quotes, resp. Interestingly, Ramus' report on Colding's 1843 paper paid particular attention to Colding's interpretation of d'Alembert's concept of lost forces; see Ramus 1843(1920), lxxvii = Marstrand 1929, 24 = Dahl 1972, 16. Besides ending abruptly, the note as printed by Meyer ends with what may be an ellipsis. My efforts to locate the manuscript of this document in the Academy's archives were unsuccessful.

idiosyncratic usage followed one that Ramus might well also have used in lecture. Thus ended a century-long process of progressive terminological hardening.

From the two passages quoted earlier in which Colding mentioned d'Alembert's principle of lost (motive) forces,[139] it appears that Colding was initially bothered by the contradiction between his initial and fundamental conviction that the forces of nature are imperishable and a fundamental principle of mechanics implying that forces might indeed be lost. His solution to this dilemma involved not only a realization that the forces "lost" à la d'Alembert (as interpreted by Poisson, Hansteen, and Ramus) represent a static equilibrium incapable of producing any kind of "activity" and hence differ fundamentally from the forces responsible for producing the phenomena of nature, but also the idea that, in certain systems of bodies, a kind of (motive) force *is* in fact lost *as such*, though it continues to exist 'unperished' in some other form. His language ("it first became clear to me") strongly suggests that he was led to conceive of the transformability of forces as the only way to avoid having to accept the possibility of their disappearance. His belief in the transformability of forces was thus rather a conclusion necessitated by his prior conviction of their imperishability than an inductive inference from the ostensibly available phenomena. As Colding recounted in 1863, his fundamental idea—that "when and wherever force seems to vanish in performing certain mechanical, chemical, or other work, the force then merely undergoes a transformation and reappears in a new form, but of the original amount as an active force"—in fact "arose at once in my mind by studying d'Alembert's celebrated and successful enunciation of the principle of active and lost forces."[140]

Ontological considerations

Colding's attachment to the atomic theory of matter and to the conception of heat as consisting of the motion of the smallest particles of matter no doubt formed an essential part of this chain of reasoning, though whether he was already convinced of the latter before he began to ponder the nature of forces, or instead came to it as a way of avoiding the apparent loss of mechanical activity in the production of heat by friction, cannot be determined from the surviving evidence. All of Colding's several accounts of the progress of his thinking have the same form, which I believe accurately reflects its historical sequence.[141] He imagined motive forces acting on the particles of matter to

139. See the passages quoted at notes 42 and 111.
140. Colding 1863(1864a), 58 = Dahl 1972, 160.
141. Colding 1843(1856), 3–4 = Dahl 1972, 1–2; Colding 1845(MS), 1; Colding 1847(1849),

produce quantities of motion. As this motion disperses itself from particle to particle, the original mechanical activity gradually disappears. But it would be against reason to think that an activity, once present, might simply disappear. (Here is where d'Alembert's principle of lost forces gave him pause, and where his prior belief in the spiritual nature of force—implying its imperishability—played a crucial role.) Hence if a force or activity seems to disappear, that must be because it has reappeared under another form, but with the same magnitude. Colding found ready corroboration of his theoretical reflections in actual phenomena:[142]

> I then first investigated the phenomena in nature such as they were [*som de forelaae*], and one will appreciate my joy in immediately making the observation that wherever in nature we see that activities disappear before our eyes during the performance of the works for which the forces are employed, there we also always see new forces appear as if from nothing; for herein lay hidden the idea I have developed in my papers that there actually exists in nature only a single fundamental force that can assume all the different forms in which we recognize the forces of nature. But with that I still had no proof of the imperishability of forces; for for that it was required that I should establish that the quantities of activity in all the new forces taken together were exactly as large as the quantities of activity in the lost force.

Colding then undertook the experimental determination of the quantitative relationship between motion and heat. It seems likely that his decision to investigate this problem in terms of frictionally produced heat owed something to his attachment to an ontology that explained heat in terms of the motion of the smallest particles of matter.

We are not yet done with staking out the bounds of Colding's conception of force. The more speculative part of his paper of 1856 throws useful light on some of the abiding ambiguity attending his never precisely defined term.[143] Noting, again, his conviction that the forces of nature are related to the spiritual and the rational in nature, Colding recognized that a demonstration that the forces of nature are actually existing entities (*virkeligt existerende Størrelser*) that are themselves imperishable does not authorize "any conclusion about the spiritual life's existence or about the human spirit's immortality."[144] Searching for evidence for this relationship, Colding argued that human beings' ability to discover the laws of nature via reason, not experience, means that human reason is capable of comprehending nature's thoughts,

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208–209; Colding 1848(1850), 129–131 = Dahl 1972, 26–27. See the presentation of this material at notes 24–27, 39, 42–43, and 68–69, resp. See also Colding 1849(1850), 169–171 = Dahl 1972, 47–50 = Colding 1849(1871), 1–3, discussed at notes 74–79.

142. Colding 1856, 137–138 = Dahl 1972, 106.

143. Colding 1856, 155–168 = Dahl 1972, 118–127.

144. Colding 1856, 156 = Dahl 1972, 118.

"that human reason is related to nature's reason, to the spirit in nature; but since nature's forces are an expression of [*Udtryk for*] the spirit that pervades nature, I believe that it is also completely well-founded when I insist that these forces are related to the human spirit."[145]

Colding addressed an imagined objection to this line of reasoning from those who hold to the materialistic belief "that the forces of nature are not actually existing entities, but merely properties of things."[146] Since this belief, fundamental to the doctrine of materialism, is false, so too must materialism itself be false. Colding counted himself among those who regard it as quite impossible "that no rational thought should underlie existence" in a world in which "every thing, from the greatest to the least, bears the stamp [*Udtrykket*] of a care and wisdom that surpasses all our understanding."[147] The almighty God who created the world so clearly purposefully and who gave human beings the ability to recognize the grandeur of nature and the reason embodied in existence could not possibly have created rational beings simply in order to deceive them by letting the world be no more than a delusion (*Blændverk*) without intrinsic truth or value. "It was this thought that I took as my starting point when, through the conclusions concerning the correspondence [*Overeensstemmelse*] between human reason and reason in nature that the immortal H.C. Ørsted first taught me to perceive and to appreciate, I came to consider that nature's forces must also be actually existing entities that are imperishable."[148]

Although Colding's reasoning is not entirely perspicuous here, he appears to have made a rough analogy between (on the one hand) human reason and the human spirit and (on the other) reason in nature, as manifest in the laws of nature, and the forces of nature through which those laws are expressed.[149] As he wrote in 1863 (in anonymous translation), "as it is obvious that it is through them [i.e., the forces of nature] only that the wisdom we perceive and admire in nature expresses itself, these powers must evidently be in relationship to the spiritual, immaterial, and intellectual power itself that guides nature in its progress; but if such is the case, it is consequently quite impossible to conceive of these forces as anything naturally mortal or perishable."[150] Divine reason manifests itself in nature through the activity of nature's forces. If those forces could lose their ability to act, then all further changes and developments in nature would come to an end—indeed, the processes of

145. Colding 1856, 156 = Dahl 1972, 119.
146. Colding 1856, 156 = Dahl 1972, 119.
147. Colding 1856, 157 = Dahl 1972, 119.
148. Colding 1856, 157 = Dahl 1972, 119. These views of Ørsted's will be examined later in this paper.
149. Cf. Dahl 1963, 176; 1972, xix.
150. Colding 1863(1864a), 58 = Dahl 1972, 160; quoted in Dahl 1972, xix.

nature might already have come to an end—in implicit contradiction with the assumption that God created the world for a purpose only to be realized in the distant future.

In amplifying his assertion that the forces of nature are not properties of bodies but free and independent entities, Colding added that they "can free themselves from matter in order to be able to traverse the universe with the speed of light;" indeed, the passage of light and heat back and forth among the heavenly bodies impels us to acknowledge "that the forces of nature, far from being bound to matter, are not even bound solely to the earth."[151] Apparently sensing the ambiguities in his understanding of forces, he noted that, as he had previously though only implicitly shown, "forces appear before us in two essentially different states [*Tilstande*]."[152] In one, they manifest themselves as the properties of bodies and substances. In the other, the force is "mobile and free, bound to matter but unbound to any individual particle of it," in which state "we encounter it as mechanical activity, as heat and light, as galvanic, electromagnetic, or magnetoelectric currents, etc., all of which...can be referred [*henføres*] to the so-called form of *living force.*"[153]

His gloss on this term indicated the direction in which he was going to carry his train of stepwise and connected associations: "The expression *living force* appears to me to be entirely felicitous insofar as it contains in itself the idea of a transitional form from a state completely dependent on matter to one completely independent of it and thus points to the higher life that I shall endeavor to show is the goal of all of nature."[154] In illustrating the relationship between these resting (*hvilende*) and mobile (*bevægelige*) forms of force, which we can transform (*overføre*) one into the other, Colding called attention to a grand fact of nature, "the law according to which everything in nature seeks to come to a union, to a leveling of all that is conflicting and opposed, to a perfectly harmonious equilibrium."[155] Yet although this union of opposites is the goal of the spirit that pervades all of nature, it is at the same time this "conflict between opposites [*Kamp imellem Modsætningerne*]" that is responsible for nature's development and through which alone "the spiritual life that is nature's goal can make progress."[156] With that, Colding was ready to sketch his teleological cosmogony.

151. Colding 1856, 158, 159 = Dahl 1972, 120, 121.
152. Colding 1856, 159 = Dahl 1972, 121.
153. Colding 1856, 159 = Dahl 1972, 121.
154. Colding 1856, 160 = Dahl 1972, 121.
155. Colding 1856, 160 ("den Lov, ifølge hvilken alt i Naturen søger at komme til en Forening, til en Udjevning af alt det Stridende og Modsatte, til en fuldkommen harmonisk Ligevægt") = Dahl 1972, 121–122.
156. Colding 1856, 161 = Dahl 1972, 122.

Colding's scenario, which he supported with the cosmogonic speculations of Kant and Laplace, has God in the beginning creating particles of matter with a tendency to approach each other—with what he elsewhere called the universal force of attraction (*den almindelige Tiltrækningskraft*) or simply universal attraction (*den almindelige Tiltrækning*).[157] This original force accounts for the striving toward the elimination of all conflict (*Strid*) and opposition (*Modsætning*).[158]

> But science teaches us, as we have seen in the foregoing, that every approach in the direction indicated by the forces leads to a freeing of the forces to what we call a "*living force*," which can appear under different forms, whereas on the contrary every distancing from the equilibrium position is impossible without sacrifice of a living force, and from this there follows the important result *that nature strives toward an ever more perfect freeing of nature's forces.*

In a like fashion the different chemical elements, endowed with different tendencies to unite with each other, combine in such a way that the resulting cancellation of the dissimilarity in their character produces not only equilibrium but also a gain in living force. Here, as always, Colding failed to take into explicit consideration the factor of separation that must be added to the attractive force in order to have a quantifiable concept about whose equivalence with living force one can meaningfully speak. Thus by emphasizing the continuity of the imagined cosmic process by which attractive force is transformed into motion he blurred the crucial distinction between forces as force (in our sense of the term) and forces as energy.

This cosmic process involved the original creation of a swirling mass of gas whose particles acquired different angular velocities as a result of expansion due to the centrifugal force and contraction due to the force of gravity (*Tyngdekraften*—his only use of the term). Thus arose not only the living force freed as a result of that contraction, but also electricity from the resulting friction between particles. Since living force could not disappear, he argued that "it combined with matter [*Materien*] and formed what we call the chemical elements, which thus took up the freed living force and preserved it for a future time. In this fashion it seems to me reasonable to suppose that matter has acquired the chemical character we find in the elements, and it can plainly be proven that the living force that became free with the change from gaseous to liquid form has been capable of developing such great quantities of heat and electricity that matter could thereby obtain its chemical properties."[159] The diversity of conditions to which matter was subjected explains

157. Colding 1856, 165 = Dahl 1972, 125 and 1847(1849), 239 (for which see the passage quoted at note 54 for the fuller context).

158. Colding 1856, 161 = Dahl 1972, 122.

159. Colding 1856, 163 = Dahl 1972, 123.

the diversity of properties the elements acquired. Thus against his occasional usage elsewhere to the contrary, Colding has here again blurred the distinction between forces and properties in the interest of telling a continuous creation story.

Plants and animals arose not by way of transformation of the forces of inanimate nature, but via the direct creation of the vital principle (*Livsprincipet*) "by the force of Him whose thought is the cause of existence."[160] Similarly, when the earth had been adequately prepared for them, human beings were created. They were to utilize the forces of nature that had gradually come into existence since the original creation of matter and attractive force "and from them develop the spiritual [and] autonomous rational life [*Fornuftliv*] that is assuredly the goal of existence."[161] Thus over time the forces of nature have freed themselves more and more from their original state of being inseparably bound to matter "in order thereby to call forth an ever higher life and more autonomous activity."[162] With human beings, the forces of nature "have reached such a stage of development that they could emerge [*fremtræde*] as autonomous spiritual beings with consciousness of themselves and with the capacity to perceive and comprehend God's infinite creative force, wisdom, and goodness and to understand that human beings' [*Menneskets*] innermost essence is related to His essence and is destined for a higher active life."[163]

Here Colding for the first and apparently only time asserted not only the imperishability of the forces of nature, but also their uncreatability:[164]

> My contention is, then, that just as the once-given activity that originally lay hidden in the universal attraction has not disappeared nor ever will disappear, but will continue to exist forever, regardless of the fact that the forces, as we have seen, continually free themselves more and more from matter and thereafter appear to disperse themselves in infinite space in the form of heat, light, electricity, etc.—neither can any new activity be formed out of nothing, but that on the contrary the increase [*Fremvæxt*] of any new force necessarily demands other forces for its nourishment and sustenance. It is my contention not only that life in general demands its nourishment, but also that spiritual activity in particular—thinking—can be regarded as work that demands its nourishment, and I do not believe I am mistaken when I express the idea that it is nature's forces in their different forms that sustain the spirit, that it is via this expenditure that spiritual activity develops....
>
> With the spiritual life's progressive development the quantity of the forces

160. Colding 1856, 164 = Dahl 1972, 124.
161. Colding 1856, 166 = Dahl 1972, 125.
162. Colding 1856, 166 = Dahl 1972, 125–126.
163. Colding 1856, 167 = Dahl 1972, 126.
164. Colding 1856, 166–167 = Dahl 1972, 126.

> of nature must thus be in continuous decline; for the sum of all these forces is an invariable quantity originally given by God!

Although for the present we have no proof that thought is a kind of spiritual work that takes place at the expense of the forces of nature—"in other words, for the proposition *that the human spirit is a new and refined* [or *ennobled*, forædlet] *form of nature's forces*"—Colding believed that one would eventually be found.[165] It would then become clear to everyone "that the human spirit is a real, autonomous entity that, independently of matter, has the capacity and power to raise itself up from the earth to Him who is the activities' cause; for nothing would be more absurd than that the forces that as such are imperishable in nature should in the human spirit be transformed [*overgaae*] into consciousness only to sink immediately thereafter into the sphere of perishability."[166]

Thus Colding's interest in establishing not merely an analogy but a causal connection between the human spirit and the forces of nature led him in the end effectively to deny the imperishability of the forces of inanimate nature, though he did not call attention to this fact. The theological concerns that motivated his earliest reflections came in the end to swamp his more circumscribed scientific principle by a grander view of the evolutionary place occupied by the conscious human spirit in its ascent from the forces of nature to God. The continuities of that progress worked against the clear delimitation of a concept of force functionally equivalent to our concept of energy. At one end of the continuum embracing his diverse conceptions of force, energy-like forces were linked with the Newtonian force of gravitation, while at the other end the evolution of spirit-like forces took away from the strict imperishability of the forces of nature. It was only between those extremes that Colding's forces and their imperishability, exemplified by his calculation of the numerical equivalence between heat and mechanical activity, look something like energy and its conservation.

Colding, Eschricht, and vital force

There remains to be considered one last aspect of Colding's multivalent conception of force:[167]

> Councillor of State *Eschricht* has attempted not long ago, in a series of lectures I had the pleasure of attending, to make good that which is incorrect in the materialistic doctrine on grounds that were most particularly drawn from

165. Colding 1856, 167 = Dahl 1972, 126.

166. Colding 1856, 167–168 = Dahl 1972, 126–127.

167. Colding 1856, 158 = Dahl 1972, 120. Similarities between Colding's and Ørsted's worldviews will be considered in a later section of this paper.

> physiology, and I owe it to truth to note that it was really at these lectures that I became disposed to set forth my favorite idea on the relationship between nature's forces and the spiritual life; but it is not physiology alone that indicates the absurdity in the materialistic doctrine; every deeper-going consideration of nature will on the whole lead to the same result, and in this regard I need merely recall *H. C. Ørsted's* "Spirit in Nature" to indicate further that the view I set forth is not any one-sided conception of nature, but on the contrary is the idea to which all branches of science lead, even though one cannot establish the idea's correctness with equal clarity via all routes.

Daniel Frederik Eschricht—named *Etatsraad* in 1853, from 1829 till his death in 1863 professor of physiology at the University of Copenhagen, and best known for his studies on whales—delivered numerous popular lectures during the 1830s, 40s, and 50s, many of which were published.[168] Thus although it has not been possible to determine just which of Eschricht's lectures Colding heard nor to know their precise content, but the relevant teachings can be pieced together reasonably well. The historiographical significance of their relationship is heightened by the fact that Robert Mayer was also stimulated not only by similar antimaterialistic physiological reflections but also by similar analogies between forces—or, more precisely, the erstwhile imponderables—and the vital force and the soul.[169]

Eschricht repeatedly addressed the relationship between the organic and the inorganic. He began an early pamphlet, *On the peculiarities that belong to organisms in general* (1832), by identifying the peculiar character of living beings as the capacity to enter into an exchange (*Vexelskifte*) of air and liquid particles. This capacity, he said, merits the name "*universal vital capacity or vital force* [almindelige Livsevne eller Livskraft]."[170] Addressing a standard topic, he noted that although chemists can analyze organic constituents into their elemental components, they have not heretofore been able to synthesize the former out of the latter, Wöhler's synthesis of urea being "a remarkable exception."[171] In the end, Eschricht came out in support of a traditional position then still widely held:[172]

168. See Eschricht [1849]–50 and 1855–59. Eschricht 1852 is his extensive reworking of Eschricht [1849]–50. During an earlier stage in my work I misread Colding as saying that he had been originally inspired by Eschricht's lectures, not that he was prompted by them to compose his essay of 1856, hence I did not adequately assess Eschricht's *Popular lectures*—i.e., Eschricht 1855–59—when I had the opportunity to do so in Copenhagen. The book appears not to be held by any American library and I have been unable to consult it since.

169. Caneva 1993, 150–152, 213 (on physiology as an opponent of materialism); 42–45, 270–271, 325 (on Mayer's views); 125–142 (on the relationship between the vital force and the imponderables). These connections will be explored toward the end of this paper.

170. Eschricht 1832, 1.

171. Eschricht 1832, 8–9, on 9n.

172. Eschricht 1832, 37–38.

> [I]f we now summarize all of this under one general viewpoint, then we cannot but recognize in every organism a controlling principle [*styrende Princip*] whose forces surpass the universal forces of nature and are subject to laws that we are far from having investigated to the same extent as the latter. It is therefore easily explicable that more or less at all times wished to abstract this principle as something independent of matter, as *life*, as a *guardian angel* (archæus), a formative drive (nisus formativus), etc. One should, however, not believe that with such an assumption one has reached the goal of our researches, where one still dares hope to be able to investigate so much.

Two years later, in the first installment of his *Handbook of physiology*, he argued similarly that although the assumption that organic processes involve nothing other than the universal forces of nature had shown itself to be a valuable stimulant to scientific discovery, one must recognize that the organism makes use of those forces in accordance with a distinctive plan; that the harmony and purposefulness exhibited by the organism imply the operation of a controlling rational force; that an idea underlies the organism's development; and that "the vital principle...manifests itself as an expression of the highest intelligence, and as an autonomous force."[173] One must be on guard, however, lest one rest content with such general conceptions as if they were adequate explanations for particular phenomena.

In subsequent writings Eschricht recognized the synthesis of urea and other compounds not as an exception recorded in a footnote but (in 1834) as a source of hope that someday art will be able to imitate organisms' powers of synthesis, even if a distinctive (*særegen*) mode of organic composition probably does exist.[174] By 1849 Eschricht had dropped the latter qualification; by 1852 continued successes had removed all doubt that "the substances in living bodies...are subject to entirely the same laws as outside of them."[175] Thus over a span of two decades one of the traditional distinctions between the inorganic and the organic was abandoned in the face of chemists' increasing skills at synthesis.

During that same period the consensus among chemists and physiologists was increasingly hostile to the notion of a vital principle.[176] As Eschricht noted in 1852, "[f]or the moment it indeed appears that most scientists have

173. Eschricht 1834–41, *1*, 33–34, 43, on 43; cf. *2*, 477–480 and 1852, 77-86. According to Callisen (1830–45, *27* [1839], 477), pp. 1–288 of the first volume appeared in 1834.

174. Eschricht 1834–41, *1*, 8–9.

175. Eschricht [1849]–50, 38–39; 1852, 63–64, on 64. From an untitled section (pp. v–vi) of Eschricht [1849]–50 dated 22 Nov 1849, it appears that the first 75 pages of the book, comprising the section "Om Livets Væsen," were published that same month.

176. On the changing status of the vital force in Germany during the 1830s and 40s see Caneva 1993, 79–125, 156–158, 208–219. In Germany, at least, the critical period of rapid change occurred in the few years around 1840.

wholly given up the vital force"; further, "[t]he vital force has, so to speak, lost its respectability [*Ansehen*], or—what is much worse for it—it has gone out of fashion."[177] Eschricht set himself against this rising tide of scientific opinion. The opening section of his collection, *Twelve lectures on selected topics concerning the doctrine of life*, addressed the "essence of life." He asked whether the development of a seed or an embryo is due to "a particular force—call it a kind of magic force [*næsten en Tryllekraft at kalde*]—elevated above all the other forces of nature" or to its distinctive original construction and chemical composition.[178] Temporarily tabling the question with an agnostic allusion to Albrecht von Haller's famous line, "Ins innre der Natur dringt kein erschafner Geist"—"No created spirit penetrates into the interior of nature"—Eschricht proceeded to give a largely descriptive account of embryological development.[179] After noting that it was formerly believed that a vital force is necessary to account for the production of distinctive organic substances but that in more recent times the whole distinction between organic and inorganic bodies seems to have fallen down, he recorded that "it is for the moment a dominant opinion that a distinct vital force is an absurdity [*Uting*]," that only the universal forces of nature play a role in the phenomena of life.[180] Nevertheless, a comparison between organisms and artificial machines shows that each owes its formation to a spiritual force lying outside of itself. Those spiritual forces are, however, of vastly different degree: "human ingenuity over against a wisdom incomprehensible to human understanding."[181]

From these reflections a grand conclusion followed:[182]

> We thus believe to see in every organism the revelation [*Aabenbarelsen*] of a force or a principle that runs through the entire life history of the species to which the organism belongs, and we believe to find that which is essential in the organism in this force, this principle, or this idea, not in the matter of which it consists, nor in its forms. We call it the vital principle. Like every other force it is only to be recognized in its manifestations, and its distinctive manifestations [are] only recognizable in matter. Just as magnetism's force propagates itself to iron, which itself can then further propagate the force to like-natured substances, every species' vital principle propagates itself further such that its corporeal representatives can also be imagined [to be] infinitely multiplied.

177. Eschricht 1852, 74, 76.

178. Eschricht [1849]–50, 1.

179. On Haller's epigram see Caneva 1993, 12, 209, and 377, n. 8. Eschricht's unattributed words were "ind i Naturens egentlige Indre trænger intet menneskeligt Øie" (2)—i.e., "no human eye penetrates into nature's actual interior."

180. Eschricht [1849]–50, 38–41, on 40; cf. 57 and 1852, 49–53.

181. Eschricht [1849]–50, 61–62, on 62.

182. Eschricht [1849]–50, 62–63.

A spirit (*Aand*) pervades and directs organic phenomena, a "peculiar controlling principle that reveals itself through the [organism's] whole life history," a life history whose chief characteristic is "precisely the harmony that rules without interruption over the whole organism in its countless smallest parts."[183] One cannot understand a painting by Rafael solely in terms of the materials used without invoking the artist's spirit.[184] Against Dutch materialist chemist Gerardus Johannes Mulder's dismissal of a vital force by way of his own analogy—Must one suppose the existence of some "battle-leading force" in order to explain why a battle takes its course?—Eschricht insisted that a battle is indeed won by the "controlling force" of the leader.[185] Against German materialist physiologist Emil du Bois-Reymond's derisive dismissal of a vital force by way of another analogy—Must one suppose the existence of some kind of "loom force" in order to explain the weaving of a shawl?—he insisted that a shawl is indeed woven only as a result of the artisan's purposeful actions, and cannot be explained merely in terms of the materials used and the universal laws of nature.[186]

In the German-language reworking of his Danish lectures Eschricht attacked German materialist anatomist Theodor Schwann's rejection of the "teleological viewpoint," embracing, as it did, a goal-directed vital force, in favor of a reductionist "physical viewpoint." Eschricht appealed to "the most essential thing, namely the inconceivable harmony of all parts and all phenomena, their completely perfect purposefulness for the preservation of the individual and the species," implicitly rejecting Schwann's own explanation—in terms of the original creation of matter by a rational being—of the apparent purposefulness he, too, acknowledged in organisms.[187] To be sure, Eschricht accepted the practical value of Schwann's "physical viewpoint" as a stimulus to the important work he and others had done in its spirit, but he could not accept it as the full truth about nature:[188]

> In my opinion one has, however, gone too far in this. A vital force in the sense of an archæus is absolutely to be rejected, not at all, however, in the sense of a principle that makes itself felt in the whole being of every animal and plant. Every vital phenomenon in and of itself may, to be sure, be explained by means of the universally operative laws of nature; yet in their totality they must surely be regarded as in fact only the external phenomena of such a principle. I cannot acknowledge an analogy between cell formation and crystallization, and, far

183. Eschricht [1849]–50, 64, 66; cf. 75 and 1852, 93, 507, 509–510.

184. Eschricht [1849]–50, 64.

185. Eschricht [1849]–50, 65–66; cf. 1852, 74–75, where he cited Mulder 1844, 67.

186. Eschricht [1849]–50, 66 ; cf. 1852, 75. Cf. du Bois-Reymond 1848, xxxix.

187. Eschricht 1852, 71; he cited Schwann 1839, 221. On these views of Schwann's see Caneva 1993, 97–99.

188. Eschricht 1852, 75–76.

> from believing that animals and plants might arise by means of a self-driven [*eigenmächtig*] transformation of elements, I must rather assume that in organisms the elements with their blind forces are only in the service of this principle. Such a viewpoint (I call it the *teleological*) appears to me to be the only one that corresponds to the character of life.

"It is," he asserted and repeated, "*an idea* that underlies the totality of the vital phenomena," making use of matter and the blind forces of nature in order to manifest itself in the purposeful phenomena of life.[189] Alluding, it would seem, to Jakob Henle, he concluded that "*the idea that underlies the development of every organism is but the idea of the species.*"[190]

Eschricht thus sought to emphasize the historical continuity of life from organism to organism down through time. With all the changes in substance and in the form of its parts that an organism undergoes, "the individual exists only in the idea of its entire developmental history;" with the change of individuals over time, "only the idea of the species persists;" and even if whole species or even whole worlds should pass away and be replaced by others, "only the idea persists, [only] the idea of all ideas persists to eternity."[191] Rejecting spontaneous generation, he believed that "out of that which is dead only that which is dead can arise; the living has its origin only in the living, the spiritual [only] in the spiritual."[192] This claim—coming in the last section of the book, headed "Life of the soul" (or "Psychic life," *Seelenleben*)—prepared the ground for his fervent (if weakly argued) case for "individual immortality," for "the persistence of the spiritual [*das Bestehen des Geistigen*] after death."[193] *Das Geistige* does not depend on *das Körperliche* for its existence, even if in fact the former only manifests itself to us through the latter:[194]

> Only in the physical phenomena does the spiritual reveal itself to human reason and we are scarcely capable of imagining it by itself alone. Nevertheless the spiritual has not arisen out of the corporeal, the latter scarcely to be regarded as older than the former; for the author [*Urhab*] of all things is itself a spiritual principle. So, too, did it emerge from our reflections that in all the changes in things the corporeal appears as the transitory [*das Vergängliche*], the spiritual the enduring [*das Bestehende*].

189. Eschricht 1852, 85–86; cf. 77–84.

190. Eschricht 1852, 86; cf. 507. Eschricht's "Idee der Art" would appear to owe something to Jakob Henle's "Idee der Gattung" of 1841; cf. Caneva 1993, 100–101.

191. Eschricht 1852, 509–510.

192. Eschricht 1852, 507; cf. [1849]–50, 57–60.

193. Eschricht 1852, 510, 511.

194. Eschricht 1852, 509.

We have here a claim for the *Unvergänglichkeit* (*Uforgængelighed*) of *das Geistige (det Aandelige)*, a claim for the persistence of the divinely created ideas that govern life, infused with an explicitly antimaterialistic sentiment. We can thus easily imagine what it might have been that Colding heard Eschricht say that decided him to "set forth [his] favorite idea on the relationship between nature's forces and the spiritual life," even if, to be sure, one of Colding's goals was to establish a developmental connection between the spiritual aspects of the universe (as manifest in human thought and consciousness) and the universal forces of nature.[195] As of 1839, when Colding likely began to reflect seriously on forces as related to the spiritual in nature, to the human spirit, and to eternal, divine reason, the scientific atmosphere was not yet charged with the kind of antimetaphysical and antitheological sentiment that became prominent during the 1840s and 1850s. It is striking, and suggestive of Colding's isolation from general trends in science, that, unlike Eschricht, he never gave any sign of recognition that his views ran counter to an increasingly assertive materialistic consensus. In any event, by 1856 he was no longer actively engaging ongoing scientific developments, but only reflecting on the progress of his own thinking as it related to his original sources of speculative inspiration.

3. LOCAL RESPONSES TO COLDING'S WORK

The commission to which Colding's paper of 1843 was referred consisted of Ørsted, Ramus, and Hoffmann. It presented its report to the Academy of Sciences on January 5, 1844 with the following précis:[196]

> The principal idea in the paper...is that the forces that are lost for mechanical effects [*Virkninger*] by frictional resistance, pressure, etc., produce internal effects in the bodies—for example, heat, electricity, and the like—and that these are proportional to the lost forces. In order to corroborate his view he has performed a series of experiments on the heat produced by friction.

This is surely a limited reading of a work that claimed that the quantity of forces (or activities) in nature is invariable, at least with regard to their nondisappearance. Ørsted also failed to make this all-important point in the comments on Colding's paper he prepared four weeks earlier. Noting that Colding was a former student who had frequently consulted with him, and hence (he said) mistrusting his own judgment, Ørsted submitted the matter to the judgment of his colleagues. He observed that two parts can be distinguished in Colding's paper:[197]

195. See the passage quoted at note 167.

196. Ørsted, Ramus, Hoffmann 1844(1845), 3 = Meyer 1920b, lxxvii = Marstrand 1929, 24 = Dahl 1972, 17.

197. Ørsted 1843(1920), lxxvi = Marstrand 1929, 23 = Dahl 1963, 180; 1972, 15. Ørsted's use

A. That lost mechanical forces should be transformed into chemical (the word taken in its broadest sense).

B. A series of experiments that show that the quantity of heat produced by friction is proportional to the frictional resistance, which experiments, however, he intends to continue with more complete means.

Here, too, the gist of the experimental part of the paper is correctly reported while the conceptual part appears glaringly misrepresented, its sweeping conceptual reach and broad implications quite unappreciated. Ørsted's further elaboration is likewise notably unenlightened, and unenlightening:[198]

> Regarding the first point, the ideas seem to me not sufficiently developed or clear. Where he speaks of lost forces it seems to me he should thereby only understand such [forces] as disappear by being neutralized [*at de ophæves*] by opposing [forces]; for otherwise it seems to me that one can insist that no mechanical force is lost. Every system of motions must, of course, according to the nature of the matter, have zero for the sum of the quantity of all of the motions. At the same time, chemical effects (the word is taken here always in the broadest sense) are probably also motions, but again such as neutralize each other. Thus friction cannot produce +E without there being aroused as much −E as is required for its neutralization [*Ophævelse*], and if one fixes one's thought first on the production of -E it is obvious that it can just as little be produced without the neutralizing quantity of +E. If one imagines heat as oscillations in the æther, then this is also a system of small motions whose sum is = 0. This holds beyond all doubt entirely generally. It seems to me therefore that his fundamental theoretical idea requires an entirely different development than it has received; but whether I perhaps have misunderstood him, I dare not say with certainty.
>
> But this does not prevent us from wishing that every investigation of the conditions under which mechanical forces produce chemical effects be zealously continued; they can lead very far. We know that the magnitude of the elastic force of air at different degrees of heat but constant volume—thus also its power [*Kraft*] to support a pressure—is proportional to the expansion these degrees of heat would give the mass of air were the original pressure maintained [*ikke ophævedes*]. The motive forces of steam seem to be proportional to their quantities of heat. If it can now be correctly proven that the frictional heat is proportional to the frictional resistance—thus also to the force employed on [overcoming] the friction [*den paa Gnidninger anvendte Kraft*]—then this is obviously a benefit to science.

Ørsted had good reason to doubt whether he had correctly understood Colding's ideas, and commentators have not known how to explain Ørsted's

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of the word "chemical" to refer to other-than-mechanical forces will be examined in a later section of this paper.

198. Ørsted 1843(1920), lxxvi = Marstrand 1929, 23–24 = Dahl 1963, 180; 1972, 15–16.

evident lack of comprehension.[199]

Ørsted's understanding of force remained tied to its classical Newtonian applications in dynamics even as he moved carelessly from forces to motions. As Marstrand remarked, Ørsted and his contemporaries "were wholly steeped in the Newtonian conception that all 'forces' must belong to closed systems of forces whose sum is zero."[200] Every action, after all, produces an equal and opposite reaction. Thus when Colding spoke of forces as *not* being lost he was using the term in a wholly non-Newtonian way that could only confuse the likes of Ørsted. Colding himself must share some of the responsibility for Ørsted's misreading, since his language of forces and activities was neither consistently deployed nor wholly free from traditional associations, as in his entanglement with the lost forces of d'Alembert's dynamics. For the rest, the quality of Ørsted's response owed much to the peculiarities of his own conception of force. Although Colding's attachment to an ontology of matter in motion did not make its full appearance in his first paper, it is significant both that Ørsted largely shared this ontology by 1843 and that neither man knew how to incorporate gravitational force into it.[201]

Marstrand suggested a religious reason behind Ørsted's not having embraced Colding's ideas:[202]

> Now H.C. Ørsted firmly believed in the invariability of the laws of nature. Many will perhaps therefore think that it would have been quite natural for him to have enthusiastically embraced Colding's conception that the forces of nature in their quantitative relationship—or what we now call their energy content—were also imperishable. But that is a superficial consideration. The same much sooner implies the opposite, because he saw more clearly than Colding that if one believed both in invariable laws of nature and in "the imperishability of the forces of nature," then there would be no room for "the spirit in nature." One could well enough retain the concept of God—as did Colding—as the ultimate cause and source of all things, but there would no longer be a question of any development of personhood. Effect would follow upon cause, and itself be cause of new effect in a ceaseless succession where everything would be predetermined, without any possibility for alteration of the individual's fate within the causal nexus all are born and live under.

There are, however, two serious problems with this explanation: there is no evidence that Ørsted had the insight attributed to him, and since Colding, like Mayer, believed in the invariability of the laws of nature, in the imperishability or indestructibility of the forces of nature, *and* in both free will and a

199. Cf. Meyer 1920b, lxvv; Marstrand 1929, 21–23; Dahl 1963, 181; 1972, xxvi–xxvii.
200. Marstrand 1929, 21 (quoted in Dahl 1972, xxvii), 23; cf. Christiansen 1915, 91.
201. See the passages quoted at and in note 79.
202. Marstrand 1929, 57; quoted in part in Dahl 1972, xxvii.

personal God, there would appear to be no compelling logic to Marstrand's reconstructed chain of considerations. Moreover, as far as their metaphysical conceptions of the world were concerned, Colding stood close to his mentor Ørsted. It was Ørsted's concept of force, not his theology, that more than anything initially separated him from Colding's conceptual world.

There is some evidence that by 1848 Ørsted had come to understand what Colding was trying to get across. Thus in his report (cosigned by Ramus and Hoffmann) on the second of Colding's papers to be presented to the Academy he wrote:[203]

> The idea which led him to his investigations and which he already stated in his first communication—and which was emphasized by us in our report of 4 January 1844—is that the forces that are lost to the obstacles against motion are not in all regards lost, but appear again in another form as heat, electricity, and the like.
>
> He has continued to develop this idea, and assumes in general that all forces without exception, when they appear to disappear, merely go over into [*gaae over i*] other forms of activity without losing anything of their true magnitude.

The first sentence represents a little fudging, since Ørsted et al. had earlier only acknowledged that the lost forces *produce* other forms of activity *proportional* to themselves, not (as here) that the former are *transformed* into the latter *unchanged in magnitude*. Significantly, they did not comment on Colding's having progressed from stating a proposition about the behavior of forces to making a general statement about their imperishability.

There remains a prima facie puzzling aspect to Ørsted's failure to pick up on Colding's sometimes crude but nevertheless creative attempts to forge a new and unified conception of the forces of nature in terms not so much of their quantitative equivalence but of their qualitative transformability one into another. For, years earlier, Ørsted himself seems to have entertained similar notions:[204]

> The constituent principles of heat, which play their part in alkalis and acids, in electricity, and in light, are also the principles of magnetism, and in such a manner we would then have the unity of all forces that, interconnecting with each other, govern the entire structure of the world, and the heretofore acquired items of physical knowledge thus unite themselves into a physics out of one piece,...for do not friction and impact produce both heat and electricity, and do not dynamics and mechanics thereby interconnect completely with each other?...Our physics will thus no longer be a collection of fragments—on motion, on heat, on air, on light, on electricity, on magnetism, and who knows what else—but we will encompass the entire world with one system.

203. Ørsted 1848, 92. Such is also the gist of the first paragraph of Ørsted's report on the third of the papers Colding submitted to the Academy (Ørsted 1850b, 91).

204. Ørsted 1803, 209–210.

In 1812 he wrote both that heat is transformed into light ("*die Wärme geht hier in Licht über*") and that the disappearance of light gives rise to heat ("*Wo Licht, als Licht, verschwindet, da entsteht Wärme*").[205] And two years after his discovery of electromagnetism he wrote that "[t]he fundamental forces of nature are indestructible [*unzerstörbar*]."[206] What was it, then, about Ørsted's conception of the forces of nature—or, as he also put it, of the different manifestations of a single fundamental force—that seems to have effectively placed him in a different conceptual world from Colding despite the appearance of their having had similar views on central issues? That is the central question to which we now turn.

4. ØRSTED'S CHANGING CONCEPTION OF THE FORCES OF NATURE

Ørsted's physics, chemistry, and natural philosophy were from beginning to end dominated *empirically* by what are often referred to as the forces or powers of nature—principally heat, light, electricity, and magnetism (the erstwhile imponderables), plus various chemical, gravitational, and other forces—and *conceptually* by an ongoing attempt to formulate a clear and unified conception of their nature and relationship. His conception of the various forces, actions, and activities of nature—the various *Kræfter*, *Virkninger*, and *Virksomheder*—changed significantly over time, and it is not safe to assume that he ever held clear and unified concepts associated with these and related terms.[207] Indeed, since he never regularly used the word force to embrace heat, light, electricity, and magnetism—typically employing no general term for what were individually generally called actions—it can be difficult to represent his thinking accurately and concisely. Hence one must pay particular attention to his usages and avoid as much as possible transcribing them into language that carries with it connotations Ørsted did not intend. Some have spoken of Ørsted's allegedly romantic belief in the "unity of forces."[208] Without a deep understanding of what Ørsted might have meant by such a phrase, unwarranted associations are likely to swamp whatever truth the assertion contains. More seriously, others have spoken of Ørsted's romantically inspired belief in the convertibility or transformability of forces.[209] Such

205. Ørsted 1812, 131, 132 = 1920, *2*, 212–213, 213.

206. Ørsted 1822b, 476 (= 1920, *3*, 167n) ~ 1852, 455.

207. For a preliminary orientation see Caneva 1997, 51–53.

208. E.g., Stauffer 1957, 34, 39, 47; Snelders 1973, 1; Knudsen 1987, 61. Cf. Caneva 1997, 41–42, and the references cited there.

209. E.g., Williams 1966, 47–48; 1974, 184; Christensen 1995, 164, 174—the latter, to be sure, not directly with regard to Ørsted, but (equally inappropriately) to Kant and the romantics to whom Ørsted was alleged to be conceptually indebted.

a notion was foreign to Ørsted's often obscurely expressed ideas—for reasons that go to the heart of his failure to understand Colding's ideas.

Under the influence of Kant et al.

All commentators have rightly noted Ørsted's conceptual indebtedness to Immanuel Kant (1724–1804), Friedrich Wilhelm Joseph Schelling (1775–1854), Johann Wilhelm Ritter (1776–1810), and Hungarian chemist Jacob Joseph Winterl (1732–1809).[210] The early Kantian influence was particularly important in shaping not only his conception of physical force, but also his general worldview of opposing forces of all kinds. Aside from the essays he composed in response to two academic prize questions set by the University of Copenhagen in 1796 and 1797—on the relationship between poetic and prosaic modes of expression and on the origin and use of the amniotic fluid—Ørsted's scientific debut in 1798 consisted of the first two of what were eventually four letters on chemistry published in the *Bibliothek for physik, medicin og oekonomie*. In the first of these he declared his support for Kant's theory of the construction of bodies out of two fundamental forces (*Grundkræfter*), which he there called forces of coherence and expansion (*Sammenhængskraft* and *Udvidekraft*).[211] But his adherence to this Kantian dynamism was limited: in the same series of letters Ørsted defended the materiality of heat and regarded light as consisting of "a distinctive element and the matter of heat."[212]

In this phase of Ørsted's theorizing, the forces of nature are solely the attractive and repulsive forces that Kant assigned to matter; they do not include heat, electricity, and the like. His understanding of force never freed itself entirely from this early association even as his ontology of nature's different forms of action long wavered ambiguously between forces and material substances, and even as his conception of the nature of heat, light, electricity, magnetism, and chemical action took a decidedly aetherial (i.e., materialistic) turn after around 1827. Thus both of Ørsted's major philosophical works of 1799—*The fundamental features of the metaphysics of nature partly on a new plan* (entitled *The first grounds of the philosophy of nature* when first published) and his *Dissertation on the form of the elementary metaphysics of*

210. Christiansen 1903, 473–484; Meyer 1920a, xv–xxxviii; Stauffer 1957, 35–43; Levere 1971, 131–139; Gower 1973, 318–319, 324–326, 339–349; Williams 1974, 182–184; Knudsen, 57–58, 61–62; Christensen 1995, 155–166; Caneva 1997, 37–41, 48–51; Wilson 1998, xv–liii. Wilson's is by far the best account yet of Ørsted's relationship to Kant and Schelling and of the conceptual background to his work in electromagnetism.

211. Ørsted 1798a, 155 = 1920, *3*, 4.

212. Ørsted 1798b, 313–314 = 1920, *3*, 7; 1799d, 173 = 1920, *3*, 25. Cf. Caneva 1997, 49 and 97, n. 87.

external nature—were basically elaborated commentaries on Kant's doctrines of motion and matter as constructed out of attractive and repulsive *Grundkræfter* or *vires primitivas*. They had nothing to say about electricity, light, or magnetism; in the paragraph of the *Fundamental features* that Ørsted devoted to heat he argued that heat must have a material cause and explicitly denied that it could be either a fundamental or a derivative force.[213] All change, all effect in the sensible world occurs only with motion, hence the force of matter must be a motive force, or rather matter *has* motive force.[214]

In a review also published in 1799 Ørsted defined a force, in physics, as that which causes or destroys motion, and concluded that all change in nature is motion since it takes place in space, that every cause of change in nature is thus a cause of motion, and that every force of nature (*Naturkraft*) is a motive force.[215] Continuing his search for appropriate terminology, he called his forces now attractive and repulsive (*tiltrækkende* and *frastødende*, *attractoria* and *repulsoria*), now positive and negative (*positiv* and *negativ*, *adfirmativa* and *negativa*); it is their conflict that produces matter via their mutual limitation.[216] By 1801 Ørsted had come to believe "that every force requires an opposite [force], and that this is necessary not because of the limitation [*Beschränkung*] of space, but that the limitation of space is a consequence of this."[217] In other words, forces must by their very nature occur pairwise in opposing couples. Ørsted was to remain attached to this fundamental notion.

Ørsted argued that the quantity of matter—as that which is substantial in nature, a subject and not a predicate—cannot be either increased or diminished; it can neither arise out of nothing (*oprinde af intet, oriri*) nor be transformed into nothing (*forvandles til intet, evanescere*), but only change its external character.[218] In a German-language summary of his views prepared under his supervision (published as *Ideas for a new architectonics of the metaphysics of nature*), this principle was extended from matter to the forces that make it up:[219]

213. Ørsted 1799a; 1799b, 38, 69–70 = 1920, *1*, 54, 71–72; 1799c, 18 = 1920, *1*, 89. Cf. Caneva 1997, 48–49.

214. Ørsted 1799b, 36 = 1920, *1*, 53; 1799c, 12–13 = 1920, *1*, 87; cf. Ørsted 1802, 23.

215. Ørsted 1799e, 813 = 1920, *3*, 43.

216. Ørsted 1799b, 36, 38 = 1920, *1*, 53, 54; 1799c, 6, 12–13, 14–15 = 1920, *1*, 85, 87, 88; cf. Ørsted 1802, 19. Elsewhere that year they were *tiltrækkende* and *tilbagedrivende* (1799e, 813–814 = 1920, *3*, 43–44).

217. Ørsted 1802, [8]; Mendel's paraphrase from an undated letter to him, as reported in his preface, dated 12 Oct 1801.

218. Ørsted 1799b, 51–52 = 1920, *1*, 61–62; 1799c, 7, 17–18 = 1920, *1*, 85, 89. Cf. Ørsted 1802, 20: "Substance can neither *arise* [entstehen] nor *perish* [vergehen]; it is invariable and its quantity [*Größe*] can thus be neither *increased* nor *diminished*."

219. Ørsted 1802, 29. While German Kantian philosopher Moritz Heinrich Mendel (1777–1813) was in Copenhagen, Ørsted communicated to him his new ideas on the subject and made available to him a Danish manuscript, which Mendel used in preparing his considerably

> *The law of substantiality* teaches that *matter* can neither arise nor perish, as *Kant* has very clearly proven. The same also holds true for the *forces*; for matter is nothing but the product of their mutual limitation, its quantity [*Größe*] is thus equal to the magnitude [*Größe*] of the forces. Thus if the force of matter were to disappear, it would be the same as if matter itself perished. But this contradicts the law of substantiality.

As we will see, not only was this apparent principle of the uncreatability and imperishability of force not to become a protoprinciple of the conservation of energy, but Ørsted soon reconceptualized force so as to disallow talk of its quantitative constancy. It is thus especially significant that he did entertain notions of conservation in some contexts. In any event, Ørsted did not continue to treat force as a substance, as did Robert Mayer.[220] Foreshadowing the kind of conceptual division long dear to him, and which in the long run probably worked against the likelihood of his creating a concept of force as energy, Ørsted identified two basic doctrines within the metaphysics of nature, one pertaining to matter, the other to the motion of matter, to which he then added a third, an "applied doctrine of motion," dealing with the motion arising from the properties of certain bodies and the mutual action of the bodies' motions.[221]

From the metaphysics of nature to a metaphysically inspired science

In 1803 Ørsted published his reworking of Winterl's dualistic chemistry as *Materials for a chemistry of the nineteenth century*, a work that, speculative as it was, marked a step from Ørsted's preoccupation with the metaphysical foundations of science to a consideration as well of the physical phenomena of scientific practice. In it Ørsted identified acidity and alkalinity as the two fundamental forces of chemistry: they neutralize each other (*heben einander auf*) and hence must be opposed to each other, just as we conclude from the neutralization of "the different electricities, magnetisms, etc.," that the latter pairs are also opposed to each other.[222] In the kind of language that would for many years characterize his treatment of heat, electricity, magnetism, and what was then commonly referred to as the chemical process, Ørsted drew the following conclusion from his review of a number of chemical reactions:[223]

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edited translation from Ørsted 1799b and 1799c; Mendel's editorial work took place, he told us, "unter Revision meines Freundes" ([6]–[7]).

220. Caneva 1993, 32–33, 36, 138, 243.

221. Ørsted 1799c, 8–9 = 1920, *1*, 86.

222. Ørsted 1803, 147.

223. Ørsted 1803, 197. The substance of heat, he added, "can *not* be *without weight*" (198). Cf. his restatement of these ideas in an undated letter to "a friend" in which he thus formulated the basic principle of the new system: "*The principle of heat is composed of the principle of acidity and that of alkalinity*" (208–209, on 208).

> Thus *whenever the principle of acidity and that of alkalinity combine with each other and hence become free, heat is produced* [hervorgebracht]; *when one of them is bound, cold arises.* No more complete proof appears to be required to justify the assumption that *the cause of heat consists of these two principles.*
>
> Besides the *changes in temperature* that arise through the *production* [Hervorbringung] *of heat out of its principles,* there can also take place *such* that derive from the *increase or decrease of the already prepared substance of heat* [des schon fertigen Wärmestoffs].

Characteristic here is the production of heat or cold through the combination or separation of opposing forces or principles, along with an obscure conception of free and bound activities (to use a more-or-less neutral word that Ørsted had not yet introduced). Also characteristic is the ambiguity surrounding the ontological status of his principles and forces, as indeed of matter itself: the construction of matter out of opposing forces, like the construction of heat out of opposing principles, blurred the distinction between matter and force, between substances and properties. His extension of his schema to include frictionally generated heat did not clarify these matters:[224]

> Just as *heat can be composed* [zusammengesetzt] *out of its two principles,* it can also *again be decomposed* [zerlegt] *into them.* A means to this is the *friction* that *collects* heat in rubbed bodies and, when they are of heterogeneous nature like *glass* and *metal, decomposes* it, such that the *former* attracts the *principle of acidity* [i.e., positive electricity], the *latter that of alkalinity* [i.e., negative electricity]....The combination of both electricities with each other is the transition of the principles of heat from difference to indifference.

Note that here, as usual, it is not a question of the explicit transformation or conversion of heat to electricity, but of the calling into manifest existence of one by the other. It was in this work, ten pages later, that Ørsted published the paragraph quoted at the end of the last section in which he expressed his conviction that the heretofore disjointed fragments of physical knowledge would be drawn together in a new system exhibiting "the unity of all forces that...govern the entire structure of the world."[225] The form in which that unification eventually took place in Ørsted's conceptualization did not lie in anything like the conservation of energy.

Ørsted's next attack on the problem of how to conceptualize the relationship among light, magnetism, electricity, and the chemical process—he strangely ignored heat in this essay, and again failed to apply any generic term to this set of activities—took a different tack, one recalling his earlier search

224. Ørsted 1803, 199. His words were "läszt sie sich auch *in dieselben wieder zerlegen.*" On the concept of indifference—much favored by Schelling and those touched by *Naturphilosophie*—see Caneva 1993, s.v. "indifference" in the index.

225. See the passage quoted at note 204.

for an architectonics of nature, a formal structure of concepts. Inspired by Ritter, Schelling, and Henrich Steffens (1773–1845), he exploited a complex collection of analogies in order to develop this relationship in terms of both symbols and an abstract hierarchy of formal relationships.[226] This essay, published in the journal of the Scandinavian Literary Society, bore the revealing title, "On the correspondence between electrical figures and organic forms." Ørsted identified the basic forms (*Grundformer*) of positive and negative electricity as a radiating point and a circle, which, taken together, represent the external limitation of an internal radiation in all directions: "Thus electricity's natural symbol [*Tegn*] is a circle with its radii."[227] These forms, he would show, are also the basic forms of nature in general, as evidence for which he adduced a wealth of analogical forms ostensibly representing combustion and reduction processes, acidic and alkaline properties, internal and external processes of vegetation, the action of sunlight on plants, contrasts between plants and animals (where imperfect plants and animals represent a kind of indifference point), and sexual opposites (where fertilization was likened to an electrical discharge). What these examples showed was that nature's formative process is an eternal conflict (*Vexelspil, Vexelkamp, Strid*) between opposing forces.[228] This is all the heady stuff of schematic *Naturphilosophie*.

Ørsted followed Steffens in associating oxygen and hydrogen with the opposition (or antithesis, *Modsætning*) constitutive of electricity, carbon and nitrogen with that of magnetism: "Carbon and nitrogen manifest themselves in chemical action, like magnetism in nature, as that which is in itself determinate and formed; oxygen and hydrogen, like electricity, as that which is eternally changeable, striving after new forms. With neither of them alone could the life of nature persist."[229] Carbon and nitrogen appeared on earth as the representatives of magnetism, laying the foundation for an electrical process that lay bound up in the determinateness of magnetism (*bundet i Magnetismens Bestemthed*) until released by the external force of light to appear as

226. Note Steffens' rejection of any explanation of the phenomena of light, heat, electricity, and magnetism—for which he had no single unifying term—in terms of some hypothetical material substance: "When the empirical experimenter materializes all force and activity [*Activitet*] in nature in this fashion, what happens—as one could foresee—is that, instead of coming closer to the scientific and organic unity [of nature], he constantly annihilates all scientific form, separates what nature has constantly united, and ascertains differences that nature knows not" (Steffens 1803, in 1968, 98–104, on 104). On Schelling's early ontologically ambivalent but materialist-tending views on force and forces, see Caneva 1993, 287–295. As Wilson well pointed out, by 1803 Schelling had come to treat them in a more formal, less substantive way (Wilson 1998, xxxii–xxxv). His account thus provides a necessary corrective to the too-restricted portrayal I gave of these aspects of Schelling's work.

227. Ørsted 1805a, 2 = 1920, *3*, 96.

228. Ørsted 1805a, 5, 10, 18 = 1920, *3*, 98, 100, 103.

229. Ørsted 1805a, 14 = 1920, *3*, 102.

the earth's formative chemical process. These relationships were illustrated by another raft of analogies between day and night, summer and winter, east and west, and combustion and reduction processes.

Ørsted then moved on to a higher-level architectonics of nature:[230]

> Schelling has shown that three moments [*Momenter*] must be distinguished in the construction of matter by attractive and repulsive forces. The first, in which the opposition of these two forces takes place only in the form of a line; the second, in which it exists in that of a surface; the third, in which these two interpenetrate each other and thus form the last dimension of space and matter, or depth. Whenever one body produces an internal change in another whereby the matter is actually reconstructed, one or several of these actions [*Actioner*] must appear anew. Thus the function of length manifests itself [*yttrer sig*] as magnetism, the function of breadth as electricity, the function of depth as interpenetration or the chemical process. Each of these dynamical processes is the interplay [*Vexelspillet*] of the opposing fundamental forces in another form. The transition [*Overgangen*] to form occurs when a magnetic, electrical, or chemical plus and minus is aroused in a homogeneous [body], or in other words when indifference goes over into [*gaaer over til*] difference.

With the three dimensions of space assigned to magnetism, electricity, and the chemical process, what is one to do with heat and light? Ignoring the former, Ørsted treated light in part as an epiphenomenon attendant upon other transitions, in part in terms of a tripartite analogy paralleling the relationship between magnetism, electricity, and the chemical process:[231]

> The phenomenon of the act of indifferentiation is light; this is clearly seen when the chemical or electrical + and – neutralize each other [*ophæve hinanden*], and the northern lights even appear to give empirical proof that the indifferentiation of the magnet likewise gives light. But if the appearance [*Fremtræden*] of light

230. Ørsted 1805a, 18–19 = 1920, *3*, 103–104 (whose correction of the text's last "Indifferents" to "Differents" I follow); translated in Wilson 1998, xxxvi–xxxvii. Where I have translated "the opposing fundamental forces" Ørsted wrote (as he usually did in all such analogous constructions) "de modsatte [i.e., opposed] Grundkræfter;" my choice was governed by the euphony of the English. Wilson's excellent account of Ørsted's relationship to Schelling (xxxii–xxxv) called attention to Schelling's concern with "formal (rather than substantial) differences" (xxxiii) and with securing "the necessary *a priori* metaphysical foundations of a universal science of nature" (xxxv), an enterprise to which Ørsted clearly felt himself drawn back. For another allusion to Schelling's notion of the different *Potenzen* in which the forces and laws of nature manifest themselves in different realms, cf. Ørsted 1809, 7: "In actuality the same laws prevail in all of nature; but this difference in power [*Potents*] in which the laws of nature appear already makes a very significant difference in the nature and presentation of the science."

231. Ørsted 1805a, 19–21 = 1920, *3*, 104–105. In a letter to Ørsted of 12 Mar 1810, Hansteen recalled a conversation he had with him (at some unspecified time) in which "[y]ou said that *gravity* [Tyngde] was *indifferentiated magnetism*" (Harding 1920, *1*, 85). As far as I know, Ørsted did not otherwise try to bring gravitation into his Schellingian schema.

> is the phenomenon of an indifferentiation, so must the disappearance of light again be accompanied by differentiation, the giving of form [*Formning*]....The first fundamental law for light is that its action [*Action*] propagates itself in straight lines, or that it comes under the form of the first dimension. When light strikes an opaque body and thereby partially disappears it necessarily arouses an internal effect [*Virkning*] in the body; for in order to neutralize the effect of the light another force must act against it that opposed it. To the act of lightening outside there thus corresponds a real act of darkening inside. Herein consists the first line's + and −. If the rectilinear ray of light is refracted through a prism there then arises a new action whose phenomenon is the spectrum of colors. The direction of this action is precisely perpendicular to that first straight line. The process of colors is thus that of the second dimension or surface. If, finally, this light that has gone over into difference falls upon a chemically easily changeable substance, there is then aroused thereby at the red pole of the spectrum of colors—as Ritter has proven—a combustion, at the violet a reduction; or, in other words, wherever light's first and second actions interpenetrate each other, the third, the chemical action, arises.
>
> Light thus manifests itself as the formative principle in nature; and that which reveals to us all forms is the same as that which itself gives everything form and color.
>
> With this short sketch I have merely wished to suggest the connection we find throughout nature between force and form.

In this conceptual work-in-progress, magnetism, electricity, and the chemical process are represented as actions, as processes, as manifestations of the opposing fundamental forces of nature, as functions of different dimensionality. Light, the universal formative principle in nature, is a phenomenon attendant upon acts of indifferentiation, i.e., of the neutralization of opposing forces; itself a process, light also exhibits various actions; itself opposed by a force, by implication light, too, would also seem to be a force. Heat, as mentioned, had no clear place in this schema. Indeed, the unresolved and fundamentally unresolvable tension between the desire to ground his concepts in an abstract and a priori metaphysics of nature à la Kant and Schelling, and the desire to do justice to a diversity of phenomena that seemed to resist easy schematization, surely did not escape Ørsted's attention. By the end of the year (1805) he would almost have abandoned any attempt to force that diversity of phenomena into a predetermined multidimensional framework as he struggled to discover the true relationship among electricity, magnetism, and the rest.

Schelling's tripartite metaphysics aside, the ambivalence and ambiguity exhibited here with regard both to the relationship among those various agencies—to use (again) a more-or-less neutral word for a diversity of terms and concepts as yet without either terminological fixity or conceptual clarity—as well as to their ontological status also characterized two other essays of Ørsted's from 1805: a review of a Danish book on electricity by

army surgeon Friderich Saxtorph (died 1808) and an essay published in the journal of the Scandinavian Literary Society entitled "New investigations on the question: What is chemistry?" At issue in the review was how to treat electricity, whether on the basis of experiment alone or on the basis of one or another hypothetical explanation. Ørsted's answer revealed both the differing demands of experimental physics and metaphysics on the one hand, and, on the other, the ambiguity attending the ontological status of any explanation of electrical phenomena.

Noting that Coulomb had treated electricity mathematically, as a theory of motion, Ørsted commented:[232]

> He indeed everywhere called the causes of electrical phenomena material substances [*Materier*]; but one could very well everywhere put forces in place of matter [*Materie*] without injury to the facts. When I wish that, in experimental investigation, one should call electrical forces what one previously called material substances, I do not thereby wish to have said that one should assume that the cause of electrical actions [or effects, *Virkninger*] are the fundamental forces of matter—this could not be assumed in advance; but I only wish thereby simply to have understood that which is active [*det Virkende*] therein, without concerning myself as to whether this active principle [*dette Virkende*] is a material substance, a pure simple force, or one composed of several. Experimental physics should always prove by means of experiment the existence of the causes it assumes; when it can no longer do this, nor get any further by means of any irrefutable conclusion, it may denote the unknown cause by a general expression, which can be transformed into a more definite one either through more successful experiments or through the help of philosophy. Such a general expression for an active cause is force; for thereby is understood nothing else than capacity to act [*Evne til at virke*]. It is quite another matter when one speaks of fundamental forces; for no experiment can decide anything about them, but must leave it to philosophy to determine whether the forces it has discovered are the simplest or whether they are still compound. One could thus then follow up the whole chain of electrical actions and perceive their connection without saying a word about electrical substances [*Materier*].

Thus the fundamental forces of nature that are the province of philosophy are not to be confused with such forces as physicists might assume in order to provide a causal explanation of experimental phenomena. The latter forces can just as well be replaced by some kind of active matter and, since active causes are by definition forces, it all comes down to the same thing. Such ontological fudging would long remain a characteristic of Ørsted's writings. Still, this passage foreshadows the way in which *activity* would later come to characterize the essence of what deserves to be called a force—at least sometimes.

232. Ørsted 1805b, 407–408 = 1920, *3*, 83–84. Most of this passage is translated in Caneva 1997, 49.

Ørsted's important essay on "What is chemistry?" had three distinct goals: a dichotomous classification of the sciences, especially with regard to the place and definition of chemistry; a specification of the meaning and properties of force, the fundamental forces of nature, and the various forces and actions we encounter in nature; and a provisional attempt to find a place for heat within a framework built around light, electricity, magnetism, and chemical forces.

A lifelong systematizer (and coiner of words), Ørsted began to sketch the outlines of a classificatory schema the general shape of which would continue to guide not only his perception of the formal structure of science, but also—and more importantly here—the way in which he habitually carved up and packaged the entities that make up the physical world. Ørsted divided physics, in the older and broader sense of *Naturlære*, into two principal parts, the theory or doctrine of motion (*Bevægelseslære*), and chemistry. (Recall his use of the word chemical "in the broadest sense" in his report on Colding's first paper.)[233] The goal of the former is to acquaint us with the objects of nature; of the latter, with the laws according to which they act. These two doctrines deal respectively with the two general ways in which bodies act on each other: mechanically, by bringing about a change in position; or dynamically, by bringing about a change in properties (*Egenskaber*) other than figure and motion.[234] This schema led Ørsted to associate force not only with the capacity to act, but also with the properties of bodies:[235]

> Bodies will thus act on each other here by means of their properties; but an active property is a force. The last part of physics will thus investigate the forces of bodies. These can be compounded of others. Therefore the ultimate forces [*sidste Kræfter*], or fundamental forces [*Grundkræfterne*], upon which all the others depend, must if possible be found out; and once these are found, one must take them as one's starting point.

One of the portentous implications of this simple schema, which Ørsted would retain for the rest of his active scientific life, is that the laws of motion and the laws of the active forces of nature are dealt with in separate parts of physics. This made it all the harder—if he had been so inclined—to embrace them all under a unified conception of force-as-energy that also included both motion and, more problematically, the spatial separation of attracting bodies that must be understood as something like potential energy if a tractable and

233. See the passages quoted at notes 197 and 198. Citing English-language works of 1790 and 1802, Heilbron (1993, 101) noted a "standard distinction between 'physics' as the study of sensible motions and 'chemistry' as the study of insensible ones," whereby electricity and magnetism were classed under chemistry.

234. Ørsted 1805c, 241, 248–250 = 1920, *3*, 106, 109–110.

235. Ørsted 1805c, 249 = 1920, *3*, 109.

universal conservation principle is to be achieved.

Chemistry deals with changes in bodies' properties. Its task is to proceed from experience to the discovery of the causes, the forces, that produce those changes:[236]

> But which are the fundamental chemical forces [*chemiske Grundkræfter*]? and which are the forms under which they act? I could easily show on philosophical grounds that the two opposing fundamental forces acted throughout nature in alternating expansions and contractions; I could show how their actions [*Virkninger*] have as many fundamental forms as space has dimensions; I could, finally, point out that all these forms must to varying degrees appear [*komme frem*] in every action [or effect, *Virkning*].

Dismissing these questions with the remark that they have been adequately answered by modern philosophers (*de nyere Philosopher*), Ørsted contented himself here with this bare allusion to the Shelling-inspired architectonics of his earlier paper.

Such questions are properly metaphysical, and in investigating the chemical forces we should, he insisted, stick to experience, which teaches us "that with every friction forces are aroused [*opvækkes*] that previously lay dormant [*slumrede*, literally 'slumbered'] in the bodies. These forces manifest themselves not only in attractions and repulsions, but, when their action is concentrated, they also produce light and heat, transform water into air, promote combustion, etc.; they thus intervene in the most forceful way in actions we previously held to be chemical."[237] Note that light and heat are implicitly classed together as effects of the actions of the underlying forces, and, of great significance, that Ørsted has explicitly introduced the notion that these (always pairwise conceived) forces lie dormant in matter, ready to be aroused and called forth by means of appropriate stimulation.

Arguing that the sought-for fundamental chemical forces are nothing but the opposing electricities, Ørsted effectively extended the domain of chemistry (in his broad sense of the word) by asserting that "the same forces that manifest themselves in electricity also manifest themselves in magnetism, although under another form."[238] He called attention to the many correspondences between the phenomena of electricity and magnetism, as well as to similarities in their respective chemical and physiological effects; Ritter's experiments again afforded him his best evidence that "the same forces are at play in electricity and in magnetism."[239] As usual, electricity, magnetism, and chemical

236. Ørsted 1805c, 251 = 1920, *3*, 110; translated in Wilson 1998, xxxvii.

237. Ørsted 1805c, 252 = 1920, *3*, 111.

238. Ørsted 1805c, 252 = 1920, *3*, 111.

239. Ørsted 1805c, 254 = 1920, *3*, 112. In a later work Ørsted recalled that it was Ritter who, on the basis of Galvani's discoveries, had already concluded "that the same forces that produce electricity also produce chemical actions"; after Volta's discovery he succeeded in showing "how

processes are grouped together as manifestations—not merely effects or actions—of the underlying fundamental forces. Ørsted consistently classed heat and light together in a way that distinguished them from electricity, magnetism, and chemical processes, for which he employed no generic term. His grouping probably reflected the fact that electricity, magnetism, and chemical processes (e.g., oxidation-reduction and acid-base reactions) were seen as involving opposing forces or principles, whereas heat and light were (*pace* Ritter) not so readily interpretable. The discovery of polarized light in 1808 did not cause Ørsted to change his basic grouping.

The inexhaustibility of force

Further discussion brought out the all-important but heretofore unstated implication that the forces that lie dormant in bodies cannot be exhausted in the production of (say) heat through friction. Thus after his conclusion that "the same forces are at play in electricity and in magnetism," Ørsted wrote:[240]

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the same forces of nature manifest themselves in chemical, electrical, and magnetic actions, in light, in heat, and even in the manifestations of life of organic bodies" (Ørsted 1811, 37, 37–38 = 1920, *3*, 184, 185). Note here the typical separate grouping of electrical, magnetic, and chemical "actions" on the one hand and of light and heat on the other, the latter not captured by any generic term. The paragraph in which these passages occurred—translated more fully in Caneva 1997, 50—was omitted from the German translation (Ørsted 1822b). In what might be called the original version of this paragraph, published two years before, Ørsted made the same remark with regard to Ritter's response to Galvani's discoveries, but with regard to Volta's discovery wrote instead that Ritter had been able to show from it "that electricity is only a phenomenon of the universal forces of nature, on which all chemical actions also depend" (Ørsted 1809, 23–24). The context of these remarks was a summary of the major events and figures in the history of physics (1809, 17–24) in which Ritter commanded more space than anyone else, including Newton. Cf. also Ørsted 1807a, 29–30 (=1851– 52, *5*, 20) ~ 1807b, 214 (= 1920, *1*, 330) ~ 1852, 314: "The dynamical theory extends...the scope [*Omkreds, Umkreis*] of chemistry far beyond its old borders. Electricity, magnetism, and galvanism come now also to belong to chemistry, and it appears that precisely the same fundamental forces that produce these actions [or effects, *Virkninger, Wirkungen*], under another form produce the chemical [actions]" (with "dynamical theory" replaced by "new theory, which we could call the dynamical" in the 1851 Danish reprinting and in the revised German text in Ørsted 1850–51a, *2*, 405). This appears to be the first time that Ørsted listed galvanism in this context, illustrating yet again the fluid character of his schemas, especially with regard to the third place-holder after electricity and magnetism.

240. Ørsted 1805c, 255–256 = 1920, *3*, 112–113; translated (in part) in Wilson 1998, xli. The translations of two phrases from this passage published in Caneva 1997, 51, have been revised here. In arguing for the existence of an "original motive principle" in nature and against the "fetishism" of those who invoke imponderable fluids, Steffens evidenced the production of heat by friction: Those who imagine heat being pressed from a body like water from a sponge fail to note that the rubbed body "appears to have an inexhaustible source [*uudtömmelig Kilde*] of the matter of heat," such that however much it is rubbed, it continues to give just as much heat (Steffens 1803, in 1968, 99–100). For other statements of the relationship between experimental science and speculative philosophy, see Ørsted 1809, 7–8 ~ 1811, 11–12 (= 1920, *3*, 163) ~ 1822b, 469.

> Heat, too, seems to be produced by the same forces; for where the two opposing electricities unite, both heat and light are produced, according to the different circumstances under which the experiment is performed. Likewise friction produces both heat and electricity, and especially the former when the conditions for an electrical indifference [*sic*] (separation of the two opposing electricities) do not occur. But if heat is nothing but the phenomenon of the same forces' struggle for unification [*Forenings-Kamp*] that are found separated in electricity and magnetism—and this will be further proven in a paper on heat—then we are obliged to assume that these forces lie dormant in every body and in each of its parts so that they must be assumed to be absolutely essential [*væsentlig fornödne*] for their constitution; for let one just try to hammer a metal wire or rod, and it will soon attain a considerable degree of heat. Let one divest it of this [heat] by cooling it in water, and a new hammering will give it new heat, and so on, as long as there still remains any unabraded portion of the metal rod or wire. One can thus deprive a body of as much heat as one wants, there nevertheless still remain dormant forces [*slumrende Kræfter*] that only need to be aroused in order to give new heat. It is thus as if the whole body could ultimately be resolved [*oplöses*] into heat. And since heat is nothing but the conflict [*Vexelkampen*] between the same forces that are active in magnetism and electricity, we thus see from the experiment with heat what role these forces play in bodies. We can at least with very good reason surmise that the demonstrated forces are the last to which any experiment has advanced. Philosophy proves still more, namely that they are the last to which any construction of matter can reach.

The repeated identification of heat as a phenomenon of the conflict of opposing forces, of their coming together, strongly suggests that in friction, too, the hidden production and immediate reunification of the two electricities, in circumstances where they cannot achieve stable separation, is the real cause of frictionally generated heat. Thus the heat produced by hammering does not in a sense *come from* the hammering; it comes from the *Grundkræfter* that constitute the body being hammered. Just as, in statics, one cannot tell from the situation of bodies at rest how great the forces are that hold each other in equilibrium, so too here one cannot estimate from the stable equilibrium of the constituent fundamental forces of a body how great *those* forces are. They might be infinitely great: effectively unlimited quantities of heat can be elicited from a body by hammering or rubbing, just as effectively unlimited quantities of frictional electricity can be elicited by the rubbing of appropriate bodies. But it is not the heat itself that has lain dormant and undetected in the body; it is the fundamental forces whose arousal is accompanied by the phenomenon of heat.

science and speculative philosophy, see Ørsted 1809, 7–8 ~ 1811, 11–12 (= 1920, *3*, 163) ~ 1822b, 469.

The conception of the inexhaustibility of force was not unique to Ørsted. In his *On the world soul* (1798), Schelling wrote that there must be an "inexhaustible source of *positive* force" that is the cause of all motion and life in the universe, that there is a "plenitude of force" that is "generated ever anew in the depths of the universe."[241] Schelling's philosophy of nature made much of the origination of all activity in the world through a process of differentiation of an original state of homogeneous indifference, a process by which forces are generated without limit in opposing (and hence potentially self-canceling) pairs.[242] Still closer in spirit to Ørsted was the dynamical crystallography that his good friend, Samuel Christian Weiss (1780–1856), appended to the 1804 German translation of Haüy's *Treatise on mineralogy*.[243] Asserting in the first thesis of his dynamical system the dependence of chemical phenomena on both an attractive and a repulsive force, Weiss stated that "the original process of nature" is in fact a "creation out of nothing," the development of oppositions (*Gegensätze*) out of nothing.[244] His second thesis and its gloss recall Ørsted's world of inexhaustible forces in conflict:[245]

> II. *Crystallization is a phenomenon of chemical repulsion in which it has not come to the dissociation, to the separation of the products from each other, but where the chemical force of separation is still restrained, without being able to reach its goal, and therefore appears merely as a tendency.*
>
> It is understandable how both of the opposing forces of chemical unification and separation in every material substance must be eternally in conflict with each other, how in the latter process the one, in the former process the other will be in excess, in a third case both will be in equilibrium....[T]he source of every opposite *in its opposite* is inexhaustible and infinite, and every product, every + and –, is capable *ad infinitum* of a new decomposition into + and –, just as every – is likewise capable of a further decomposition into – and +.

It is thus clear how the origins of Ørsted's philosophizing in the dynamism of Kant and Schelling made it easy—indeed, necessary—to think of forces as indefinitely renewable, as inexhaustible, though it is precisely that inexhaustibility that renders moot any question of their quantitative unchangeability. The indestructibility of force is not the same kind of thing as the conservation of energy.

241. Schelling 1798/1806/1809, 381 ("eine unerschöpfliche Quelle *positiver* Kraft"), 464; cf. 463 ("der unerschöpfliche Quell positiver Kraft"). Cf. Ørsted 1811, 2 (= 1920, *3*, 156) ~ 1822b, 459 ~ 1852, 448: "Throughout nature we discover an activity [*en Virksomhed, ein Wirken*] that knows no rest. What appears to our eyes to be stillness is only a slow change."

242. Cf. Caneva 1993, 284, 294–295.

243. Cf. Caneva 1997, 55.

244. Weiss 1804, 368–369, both on 369.

245. Weiss 1804, 371–372.

Ontological uncertainties: Forces or motions?

Rather than calling attention to this aspect of Ørsted's conception of force, Andrew Wilson's analysis of Ørsted's indebtedness to Schelling emphasized the form-dependent, the dimensional aspects of Ørsted's thinking, i.e., the architectonic relationship Ørsted sought between force and form. To that end he quoted from a passage in Ørsted's "What is chemistry?" The principal significance of this passage is less its clear dependence on Schelling's mode of abstract analysis than the fact that, with the exception of perhaps a single later reference, it marked the effective end of Ørsted's involvement with this kind of tripartite schematizing.[246] It also illustrates his continuing attempt to specify the proper relationship among heat, light, electricity, and magnetism—the formerly prominent "chemical process" having here almost disappeared from sight—as well as the relationship of all of them to the hypothesized fundamental forces:[247]

> A brief overview of what we know about the actions of these forces is already sufficient to indicate to us the possibility that all of nature's most different forces can be traced back [*tilbageföres*] to these two fundamental forces. Indeed, how can there be three more different actions than heat, electricity, and magnetism! And yet these all depend on [*beroe paa*] the action of the same fundamental forces, only under different forms. Magnetism acts only in a *line* that is determined by the two opposite poles and the intermediate equilibrium point.[1] The purely electrical action follows only the *surfaces*.[2] Heat acts equally unhindered in *all directions* in a body. No one can deny that this difference really exists. That it is essential, only an extensive investigation can rightly convince

246. I thus do not agree with Wilson (1998, xxxix) that Ørsted "remained convinced that geometrical arrangements of the *Grundkräfte* were the key to demonstrating the underlying connection between, and common cause of, different physical effects and to transforming chemistry into a mathematical science." The exception alluded to above is Ørsted 1807a, 33 (*omitted* from the reprinting in 1851–52, *5*, 20, where it would otherwise have come) ~ 1807b, 216 (= 1920, *1*, 332; *omitted* from the reprintings in 1850–51a, *2*, 407 and 1850–51b, *3*, 162, as well as from the English translation in 1852, 315), after he criticized the attempt to identify the material elements of chemical substances: "If, on the contrary, everything depends on certain fundamental forces and the forms in which they manifest themselves, then one will have to be able to find the principle for these forms and to show which and how many there are possible, more or less after the pattern that *Schelling* has given us by presenting them according to the three dimensions in space." He did not further develop these ideas here; the fact that he omitted this paragraph from the 1851 reprintings strongly suggests that, at least by then, he wished to distance himself from these Schellingian speculations. Note also Ørsted's omission of a favorable comment on Schelling's *Naturphilosophie* and its potential importance to the experimental scientist from the 1822 German translation of a work published in earlier incarnations in Danish in 1809 and 1811 (Ørsted 1809, 24; 1811, 38 = 1920, *3*, 185; cf. 1822b), and the omission of a reference to Ritter cited in note 239.

247. Ørsted 1805c, 256–258 = 1920, *3*, 113–114; the first paragraph translated (in large part) in Wilson 1998, xxxviii. This passage is continuous with the one quoted at note 240.

us. Yet it can hardly do other than arouse the greatest attention that these three actions fall precisely under forms that correspond to the three dimensions in space and to their expressions: line, surface, body. That there cannot be more fundamental forms for the action of the fundamental forces seems to me obvious at first glance, [although] only philosophy can give complete certainty in this matter.

But where heat attains its highest manifestation of force [*sin höjeste Kraftyttring*] it is transformed [*forvandler sig*] into light, just as light, where it loses its intensity, is transformed into heat. The best known facts speak so strongly for this that one must ascribe it to a theoretical confusion that one has heretofore not always recognized it. With this change heat is led to radiate out in all directions in straight lines, yet in such a way that it thereby fills up space. Heat, which previously spread out under the form of corporality, has now in a *higher mode* again come under the form of a *line*. The process of color is light's spreading out into a *surface*; but in a *higher form* than the electrical *surface form*. The proof of this is not that it is principally surfaces that show colors, but that the white light ray *is spread out* as it goes over into rays of color. Finally, under this, its surface potentiation, light arouses a *combustion* and a *reduction process*, as Ritter's experiments with light show. Anyone can easily see that this is a process under the same form as heat but of a higher order.[3]

. . .

1. Of course, a body can be magnetized in several lines, but then we always rightly regard these as produced by several different magnetic processes.

2. When it acts otherwise it is already in transition to [*paa Overgangen til*] magnetism.

3. That electricity and magnetism cannot produce chemical activity directly, but only after having been potentiated, I shall show at another occasion.

In accord with the spirit of Schelling's *Naturphilosophie*, the *tracing back* of electricity and the rest to the two fundamental forces of nature must not be understood in a *reductionistic* fashion. Ørsted spoke consistently of electricity and the rest as *manifestations of the action* of those fundamental forces: the former are thus unified formally without being formally identical. Heat appears here to have usurped the form of three-dimensionality formerly assigned to the chemical process. At the same time both heat and light are treated as manifestations, as "expressions" (*Yttringer, Aeußerungen*), of the same force raised to different powers, light itself having both one- and two-dimensional manifestations (its surface form somehow higher than that of electricity) and capable of producing a three-dimensional chemical process (the corporeal form of which is somehow higher than that of heat). Ørsted would soon abandon his fascination with this kind of complex hierarchical structure even as he remained perennially concerned with the question of the interrelationships among the various forces and activities of nature. Resonances would remain, but he seems to have come to the conclusion that the kind of closed formal system he toyed with here would never be capable of adequately comprehending all of the phenomena of interest.

He turned his attention for a time to the problem of the mode of propagation of electricity, elaborating on his basic conception of electrical activity as manifesting a struggle between the two opposing electricities to achieve by turns separation or differentiation and unification or indifferentiation. Basing his schema for "the internal mechanism of the propagation of electricity" on the further assumption that each electricity produces or "calls forth" its opposite (*frembringer det Modsatte af den, ihren Gegensatz hervorruft*), Ørsted imagined electricity to be propagated by means of an alternating undulation of positive and negative.[248] Not only must magnetism—like electricity, dependent upon an initial polarization—also be propagated in an undulatory fashion, but this same schema for the noninstantaneous undulatory propagation of actions (*Wirkungen*) must be quite general in nature; it is found, for example, in the propagation of sound through solid bodies and through air.[249]

This mode of propagation, with its underlying ontological ambiguity, would long remain a feature of Ørsted's physical worldview. In writing of "de afvexlende Veje af det Positive og Negative" ("die wechselnden Wogen des Positiven und Negativen)" he avoided specifying just what it is that manifests these opposing qualities.[250] If his usual talk of the constitution of matter out of the fundamental attractive and repulsive forces of nature and his treatment of electricity and magnetism as manifestations of them would seem to imply an ontology of forces, his illustration of the mechanism of propagation by means of sound and Chladni figures—patterns of lycopodium powder formed on vibrating plates—might rather suggest, by analogy, that electricity and magnetism are also disturbances of some material substance. With respect neither to the formal relationship among the forces and activities of nature nor to their ontological status did Ørsted ever achieve a clear and consistent formulation. He had occasion to reconsider the concept of force, and to revisit the question of what part of science their study belongs to, from a general theoretical standpoint in a series of didactic works beginning with the publication in 1809 of the first and only volume of his textbook, *The science of nature's universal laws*.[251] The introduction, "General reflections on science," was revised and reprinted in several formats during the next forty years.[252]

248. Ørsted 1806a, 268–271 ~ 1806b, 292–294 (= 1920, *1*, 267–268) ~ 1806c, 369–371; cf. Caneva 1980, 128–129 and Wilson 1998, xli–xlv (a good account). In Danish Ørsted described that propagation as *bølgedannet* (271), *oscillatorisk* (272–273), and *bølgeagtig* (274), in German as *undulatorisch* (295 *bzw.* 269) and *oscillatorisch* (296 *bzw.* 269).

249. Ørsted 1806b, 297–299 (= 1920, *1*, 270–271) ~ 1806c, 372–373; the shorter Danish "fragment" considered only magnetism (1806a, 274–275).

250. Ørsted 1806a, 270–271; 1806b, 294 = 1920, *1*, 268.

251. Ørsted 1809. The book was printed already in 1807, but the edition burned during the British bombardment of Copenhagen (Meyer 1920b, cl).

252. Ørsted 1811 (*First introduction to the universal physics of nature*), 1822b ("On the study of the universal physics of nature"), 1847 (*The spirit and essence of the universal physics of*

Ørsted was long and strongly attached to these ideas.[253]

The "General reflections" kept the gist of Ørsted's earlier distinction between the theory of motion and chemistry, except that now he called the two divisions of physics *Bevægelseslære* and *Kraftlære*, the theory (or science) of motion and the theory (or science) of force.[254] The former represents the mechanical part of physics and deals with the external (*udvortes*) changes of bodies, i.e., with respect to their place and relative position, i.e., their motions. The latter represents the dynamical part of physics and deals with the internal (*indvortes*) changes of bodies, i.,e., with respect to the properties with which they act upon each other, i.e., changes in force.[255] The theory of force investigates properties in terms of their activity (*Virksomhed*), and we call an active property a force.[256] Thus, as before, the study of motion is separated from the study of forces and the manifestations of their action in electricity and the rest. Ørsted referred to a third division dealing with the laws for the action of forces in conjunction with motions, but since it had not yet received adequate elaboration it properly belonged to the dynamical part of physics.[257] Apparently still feeling some ambivalence here, he added a gloss in smaller indented type: "That the mechanical part deals with motive forces should not give occasion to confuse it with the theory of force, just as little as when the theory of force deals with motions produced by the internal forces; for in the one case the overall goal is to determine the laws of motion, in the other case,

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nature). "Universal physics of nature" is, to be sure, a rather free rendering of "almindelige Naturlære" and "allgemeine Naturlehre," but I believe it captures the spirit of the Danish and German phrases.

253. Although I have made an attempt to track changes in Ørsted's texts, logistical problems attendant upon the difficulty of gaining access to them means that the absence of a cross-reference does not necessarily mean that one might not be appropriate.

254. Ørsted 1809, 1–32.

255. Ørsted 1809, 16–17 ~ 1811, 14–15 (= 1920, *3*, 165–166) ~ 1822b, 473. For his continued attachment to chemistry as the name for that part of physics that deals with forces, see 1811, 15 (= 1920, *3*, 166) ~ 1822b, 471, 473–474. Noting that all chemical actions can be referred back to the manifestation (*Yttringen, Aeußerung*) of two principal forces (*Hovedkræfter, Hauptkräfte*), he added that the freest manifestations of these universal opposing forces are found "in the electrical, galvanic, and magnetic actions" (1811, 15–16 [= 1920, *3*, 166] ~ 1822b, 474). The historical and biographical aspects of Ørsted's division of forces into internal and external are suggested in an anecdote recounted by his former student, Carsten Hauch (Hauch 1852, 126–127). Shortly after he'd become a student in 1808, an older scientist told him he had gotten very angry at hearing Ørsted say that "Newton and Kant were the two poles around which modern science revolved." Hauch's interpretation of his meaning was "that just as Newton explained all external motion in the universe with two forces, so too with regard to internal activity had Kant come to the same result."

256. Ørsted 1811, 15 (= 1920, *3*, 165) ~ 1822b, 473.

257. Ørsted 1809, 16 ~ 1811, 16 (= 1920, *3*, 166–167) ~ 1822b, 474.

on the contrary, the laws of the forces."[258]

Anticipating the objection that it does not make sense to treat the mechanical part of physics before the dynamical—internal forces being the cause of all external phenomena, it is impossible for a body to set another in motion without these (as yet unstudied) forces—he countered that the empirical method of science always begins with the external in order to penetrate the internal, with the determined and the dependent in order to get at the essence of things.[259] Ørsted noted one further difference between these two branches of physics: "The theory of motion has been transformed almost entirely into mathematics. The theory of force awaits the inventive spirit that can lead it to the same point; for the internal forces manifest themselves [*vise sig, zeigen sich*] only in time and space, and their laws can only be regarded as completely known to us when we can represent all the relationships occurring in them in their proper magnitude."[260] In the event, successful mathematization of the forces belonging to Ørsted's dynamical part of physics actually took place only by breaking down the barrier he had erected between it and mechanics. The inventive spirit at work here was his student, Colding.

Ørsted's introduction of his conception of force in the second section of his textbook of 1809 proceeded on familiar terms.[261] The mechanical atomic theory, whose widespread acceptance was owing especially to the fact that the theory of motion was the most developed part of science, had, he noted, recently been challenged by Kant's dynamical system based on the doctrine that matter fills space by means of certain fundamental forces. This latter system, according to Ørsted, better accorded with the findings of experimental *Naturlære*, even if, to be sure, the latter did not need to presuppose its correctness. The basic property of bodies of taking up space led us to recognize in them a force of expansion (*Udvidekraft*), just as the property of bodies known as gravity (*Tyngde*) prompted us to generalize to the assumption of a universal force of attraction. We thus recognize that the very existence of bodies requires us to assume as the two fundamental forces of nature an expansive and an attractive force. Experience further informs us of the existence of a cohesive force (*Sammenhængskraft*) in matter. In a self-

258. Ørsted 1809, 17; cf. 1811, 16 (= 1920, *3*, 167) ~ 1822b, 474. In the later versions the distinction was between the "*forces* that produce motion," treated in the mechanical part, and the "*motions* produced by these forces," treated in the dynamical part (italics as in the 1811 wording). But "produced by the *internal* forces" is not the same thing as "produced by *these* forces," where "these" referred to the motive forces of mechanics (the italics here are mine). Ørsted thus blurred the distinction between the very different kinds of forces dealt with by his mechanical and dynamical physics.

259. Ørsted 1809, 17 ~ 1811, 16 (= 1920, *3*, 167) ~ 1822b, 474–475.

260. Ørsted 1811, 23 (= 1920, *3*, 173) ~ 1822b, 483 ~ 1847, 13 ~ 1852, 461.

261. Ørsted 1809, 32–62 ("The universal properties and relationships of bodies").

contradictory account of inertia as a fundamental property, Ørsted argued that all change in bodies is owing to their possession of certain forces that are either motive (*bevægende*) or internally transformative (*indvortes omdannende*), such motive forces being exclusively those of expansion, gravity, and cohesion. Thus as regards mechanical interactions, the forces by which bodies act upon each other are also those by which the bodies exist in space "as *self-contained wholes* [sluttet Hele]," whereas in dynamical interactions "*force* acts against *force immediately*, and endeavors to achieve a common union and equilibrium, either by forming a new whole or by generating from a previously existing whole two or more new wholes different from it."[262] The latter processes implicitly represented the mode of action of the familiar threesome of electrical, magnetic, and chemical forces. Again we have an analysis of forces primarily concerned with their descriptive classification into distinct species and with certain formal aspects of their relationship to each other. Kirstine Meyer, the sympathetic editor of Ørsted's three-volume *Scientific papers*, criticized Ørsted's book for defects in its presentation of mechanics and for imprecision in the definition and application of important concepts, adding that "the concept of force is particularly vague and unsuited for mathematical treatment or practical calculations."[263]

In 1812 Ørsted published his most extensive and important treatment of the relationship among the two fundamental opposing forces of nature, chemical actions and forces, and the actions (*Wirkungen*) of electricity, heat, light, and magnetism—to name them in the order in which he treated them. His book, *View of the chemical laws of nature, gained through recent discoveries*—initially published in German, reissued in a much revised French translation the following year under the title *Researches on the identity of the chemical and electrical forces*[264] —embodied his broad conception of

262. Ørsted 1809, 58.

263. Meyer 1920b, clii.

264. Then as now there has been some uncertainty as to the extent of Ørsted's authorship of the very different French reworking of his book. His explanation in a letter of 5 Jul 1816 to Thomas Thomson, in which he said he was directing his publisher in Paris to send Thomson a copy of his book, should settle any questions: "L'original allemand sera moins intelligible pour les étrangés [*sic*] que la traduction française, que j'en ai fait avec Mr. *Marcel de Serres*. J'y ai refondu entièrement plusieurs articles pour les rendre plus intelligibles d'abord à mon traducteur et ensuite aux lecteurs français. La traduction française a ausi l'avantage sur l'original que j'y ai fait quelques corrections dans ma théorie de la lumière. Quelques journalistes français qui paraissent fort intimes avec Mr. de Serres ont voulu faire croire au public que le traducteur avait quelque part dans la matière de l'ouvrage, ce qui est absolument faux et même impossible, comme Mr. de Serres, qui est Professeur d'histoire naturelle n'a pas des connaissances chimiques plus étendues que celles nécessaires à sa profession" (1816[MS], [1]). See also the account in his autobiography (1828, 530). Here again logistical problems—in particular, the rarity of the French edition—made it impossible to compare the two books on every point, especially as my reading of them changed.

chemistry as the all-embracing science of force (*Kraftlehre*) whose goal is to reduce all chemical actions to the primordial forces out of which they arise, to show "that all heretofore investigated chemical changes can be referred [*sich zurückführen lassen*] to two forces of nature of universal extent."[265] (Instead of the usual term *Grundkräfte* consistently employed elsewhere in the book, he here called those "primordial forces" *Urkräfte*, a word he rarely used, especially in the plural.)

He promised to show how the manifestation of the chemical forces in galvanism, "in their freer activity," demonstrates their "identity with the electrical [forces]" under a different form of action (*Wirkungsform*), from which we are justified in concluding "that the electrical forces, just like the chemical, are only two and at the same time opposing, that both are of universal extent and, aroused by external forces out of the relative rest in which they are found in bodies, can go over into activity [*zur Thätigkeit übergehen*]."[266] In imagery rich with the tropes of *Naturphilosophie*, Ørsted situated those forces within a grand scheme of the gradual development of the structures and activities of nature as a unified whole subject to eternal laws. Nature creates each of its works "out of the forces that lie dormant in it [*aus den darin schlummernden Kräften*]," only to destroy it "in order to be able to exhibit the eternal activity and the eternal law in new creatures [*Geschöpfen*]."[267] Through this process of continual transformation, nature causes its forces to appear under a variety of forms of action. The same universal forces appear in the organic realm in accordance with a "higher principle of unity" as "new forms of action of the known [forces]."[268] All the different substances we find on earth represent merely "resting places of the activity with which nature proceeds from work to work in the formation of the earth."[269]

265. Ørsted 1812, 5, 7 (quote) = 1920, *2*, 38, 39; cf. 275 *bzw.* 158. The corresponding passages in the French edition appealed to mechanics as a model for a future mathematized chemistry based on the actions of certain *forces primitives* (1813, 2–5).

266. Ørsted 1812, 7–8 = 1920, *2*, 39–40; cf. 1813, 7, where he added that the electrical and chemical forces also have the property of destroying each other ("la propriété de s'entre-détruire l'une l'autre"). For his later restatement of his basic points, see 1812, 114–115 = 1920, *2*, 88. See Williams 1966, 51–63, for a discussion of Ørsted's conception of forces drawn primarily from Ørsted 1813. For Wilson (1998, xlix), *Wirkungsform* is the "central concept" of the book. On Schelling's and Steffens' use of the concept of *Form*, see Caneva 1997, 421.

267. Ørsted 1812, 65–66 = 1920, *2*, 66. Since the pronouns that refer to *die Natur* have feminine form because the noun itself is grammatically feminine, there is no way in German to indicate whether the metaphoric "she" is warranted over the merely grammatical "it."

268. Ørsted 1812, 236 = 1920, *2*, 142.

269. Ørsted 1812, 68 = 1920, *2*, 67. This image of nature's productivity underlay his defense of the alchemical comparison between metals and planets: "For if metals have developed along with the earth, the latter, however, along with the other heavenly bodies of our solar system (comets and planets with their satellites): how very probable—indeed, one might say certain—is it not that both developments have proceeded according to the same laws, only according to different powers [*Potenzen*]!" (1812, 291 = 1920, *2*, 166).

In investigating the chemical forces of nature, Ørsted began with their most striking manifestation (as fire), their freest and strongest activity (in combustion). He thus handily identified the two opposing chemical forces of combustibility and comburence, *Brennkraft* and *Zündkraft*—in French, *force de combustibilité* and *force comburente*—the former characterizing things that burn, the latter things that support combustion.[270] Combustion itself is produced through the endeavor of the forces to unite, a process in which they neutralize each other's action (*sich einander wechselseitig aufheben*). This *Aufhebung der Kräfte* is "no internal annihilation, but only a limitation whereby their manifestations [*Aeußerungen*] become unnoticeable. The opposing chemical forces are just as present in a combusted body as are the mechanical forces in a body that is held in equilibrium by opposing forces."[271] Ever sensitive to the vexing problem of the proper ontological interpretation to be given these forces, even as he revealed himself incapable of solving it, Ørsted conceded "that we do not at all believe that we have explained anything with them. For the time being we leave entirely unsettled what these forces are, whether they are either something autonomous [*Selbstständiges*] or merely modifications of other forces or of material substances [*Materien*]. We are only employing the common usage of calling every active property a force."[272] And again:[273]

270. Ørsted 1812, 79–80 = 1920, 2, 72–73; cf. 1813, 78. In a classification of chemical substances he traced the predominant *verbrennungshervorbringende Thätigkeit* (*activité ignifère*) of some to their composition out of a *brennbare* and a *zündungsfördernde Eigenschaft* (*force de combustibilité* and *force comburente*), the predominant *neutralisirende Thätigkeit* (*activité neutralisante*) of others to their composition out of the opposing properties of acidity and alkalinity (1812, 73 = 1920, 2, 69; 1813, 73). Ørsted was perennially in search of appropriate terminology.

271. Ørsted 1812, 81–82 = 1920, 2, 73; cf. 1813, 79. With regard to "pure combustion," in which the two chemical forces unite immediately, Ørsted called philosophers' attention to the fact that "this unification of forces, when it takes place thoroughly undisturbed, must be without any perceptible effect [*Erfolg*], and thus this action [*Act*] appears to the senses only insofar as it is disturbed or broken. In that pure unification of forces are thus light, heat, and combustion, but in a transparent and unseparated state inaccessible to our senses" (1812, 282, 283 = 1920, 2, 162).

272. Ørsted 1812, 81 = 1920, 2, 73; cf. 1813, 78–79: "For the rest, we do not pretend to explain anything thereby, but only to allow the facts to be understood in a simpler and more general manner. Thus we shall not decide here whether these forces are primitive forces, or whether they are merely modifications of other forces, or even whether they are imponderable fluids. We only call the unknown cause a force, without deciding anything about its nature. In this we follow the example of Newton, who, in accord with the same principles, calls *attractive force* the cause that makes bodies heavy with respect to each other." Gower (1973, 341) signaled the significance of "Oersted's inability to decide whether forces are peculiar properties of matter or whether they are supra-sensible non-spatial entities causally responsible for the existence of matter."

273. Ørsted 1812, 114–115 = 1920, 2, 88; cf. 1813, 109–110, where the roughly corresponding passage ends with "or, finally, whether these forces are spread out [*répandus*] in space without being bound to points similar [to the molecules of bodies]." In the book's last

> For the rest, where we speak of fundamental forces we wish to say nothing more thereby than to designate the simplest active and efficient agency [*das einfachste Thätige und Wirkende*] that shines through in our experiences. What these forces are originally belongs to properly speculative philosophy to make out. The highest [point] we can come to on our path is this: that those forces, as opposites [*Gegensätze*], must again have their higher unity...[W]hatever view one may have of the nature of these forces—let him even bind each of them to a distinctive subtle matter—he will still be able to investigate with us the series of natural laws that we will attempt to establish here.

Ørsted's indecisiveness amounted to a kind of de facto positivism.

Forces and their forms of action

In the pivotal section on "The electrical forces regarded as chemical," Ørsted asserted that we now know "that in the electrical actions we again find the same forces that also produce the chemical actions—and [we find them there] in their freest outwardly directed activity," in their "freest form of action."[274] Those electrical actions reveal their dependence on two opposing and mutually canceling properties, and as active properties (*thätige Eigenschaften, propriétés actives*) we call them forces, "without thereby wishing to further determine their nature."[275] In accordance with his conception of the interaction between the opposing fundamental forces, these two electrical forces can mutually bind each other in such a way that neither is externally perceptible, "and a body could thus contain, long undetected, an immeasurable quantity of them."[276]

Experiments with all kinds of substances in fact demonstrate that all bodies contain the electrical forces, which are imperceptible only because they are in equilibrium. As he had in 1806—and with the same ontological

section Ørsted repeated his contention that the laws of nature are empirically discoverable even if we can't by those means also discover the true essence of the underlying causes: "One will see that it has everywhere been our intention to discover laws, not to indicate causes, which for the rest derive easily from the discovered laws. It would not be difficult, as regards the causal [aspect], to translate our view into another, e.g., instead of forces to assume two electrical substances [*Materien*], indeed to compose in thought all bodies out of two such elements. Aside from a few difficulties, one would on such a view be able to utilize all of the lawfulness established here" (1812, 288 = 1920, 2, 164).

274. Ørsted 1812, 133 = 1920, 2, 96. Thomas Thomson's sketch of Ørsted's views noted his ontological indecisiveness: "The metaphysical part I do not fully understand; nor have I been able to make out whether the author's electrical forces be substances or qualities" (Thomson 1815, 8; quoted in Gower 1973, 339). Thomson was, to be sure, judging on the basis of secondary reports; he hadn't been able to consult Ørsted's *View*.

275. Ørsted 1812, 133–134 = 1920, 2, 96; cf. 1813, 126.

276. Ørsted 1812, 134 = 1920, 2, 96–97.

fudging—Ørsted explained the propagation of electricity through solid bodies and through space in terms of the alternating disruption and reestablishment of the internal equilibrium of the universally distributed electrical forces.[277] In good conductors the momentarily separated opposing forces neutralize each other so quickly as to be imperceptible, whereas in poor conductors—we would say nonconductors—the separated electricities can be detected by means of an electrometer. Having gone through yet another rehearsal of the grounds for concluding "that the chemical and electrical actions are produced by the same forces," Ørsted cautioned his readers not to draw any unjustified conclusions about the identity of these and other actions: "But since we also find that the mechanical filling of space may also derive from the same [forces], and in what follows we will find the same forces in all other actions of bodies as well, it is thus necessary that we take care lest we mix everything together. We shall thus not jumble together the electrical action, the chemical, the action of heat, and light, rather we shall regard them all as different forms of action of the two universal forces. But the forms also pass over into each other through many stages [*Stufen*]."[278] Thus in Ørsted's conceptualization it is less correct to say that the forces of electricity and magnetism can be converted one into the other than to say that electricity and magnetism are phenomena that manifest different forms of action, different degrees of disequilibrium, of the same two fundamental forces. And since for him those fundamental forces are undetectable as long as they lie dormant in a state of neutralized indifference, a body may well contain an infinite and inexhaustible amount of force.[279]

In the continuation of the passage just quoted Ørsted sought to characterize the differences among the various forms of action in terms of an obscurely deployed concept of latency:[280]

277. Ørsted 1812, 138–140 = 1920, 2, 98–99; cf. 1813, 130–131, where the language of "continuous decomposition and recomposition" more strongly suggests some kind of material substrate. By the same token, the language of the German original, in its abiding ambiguity, suggests nevertheless some kind of force-based ontology: From the conclusion that the propagation of electricity takes place in terms of an alternating disruption and reestablishment of an equilibrium of forces, he further concluded "that *the electrical forces are conducted only by themselves* (*namely by other electrical forces*). But whoever shares with us the conviction that it is precisely these forces by means of which space becomes corporeal, must surely find this expression equivalent to the customary one, that *bodies conduct the forces*" (1812, 140 =1920, 2, 99).

278. Ørsted 1812, 150–151 = 1920, 2, 104; cf. 1813, 141–142, where it is stated that the differences between the various actions (to which he here added magnetism) "will depend on the interior mechanism of the action, on their form of activity," the language of the French edition thus again suggesting a more material interpretation of the actions in question. On the differences between the two editions see Caneva 1980, 128–129 and the notes thereto.

279. Caneva 1997, 52.

280. Ørsted 1812, 151 = 1920, 2, 104.

> Thus the actual fundamental form of electricity is the free dispersal of the two forces through their forces of expansion and attraction. In the electrical charge this is already mixed up more with the self-containment [*Insichseyn*] of the chemical form of action. This happens still more in electrophorical actions, and one finally comes to the complete binding [*Gebundenwerden*] of the forces in electrical explosions, decompositions of air and of oil, decomposition of water, etc. But in order to recognize more precisely the distinction among the forms of action it will be necessary to have considered the others as well. But the next thing for us to consider here is heat.

Nor did a later brief characterization of the forms of action of the sensibly undetectable light, heat, and combustion accompanying a "pure unification of forces" appreciably clarify the obscurity of his thought: "Self-containment is here the proper form of light. Mutual interpenetration [*das wechselseitige Ineinandergreifen*] is the form of heat, the identifying of the activities that of combustion. But we leave this investigation to the philosophers."[281]

Ørsted first addressed the question of heat in terms of the heat generated when electricity passes through poor conductors, or when a body is forced to conduct more electricity than it would have done freely, his image again being that of a succession of ruptures and reestablishments of equilibrium, of an internal struggle between opposing forces.[282] Rejecting material and fluid theories of heat for all the standard reasons, he next considered the production of heat through percussion and friction, noting that we already know from electrical experiments "that the forces can be disturbed in their equilibrium by mechanical action [*Einwirkung*]."[283] He interpreted experiments that seemed to show that a coin that has been stamped to its maximum compression does not yield more heat through continued stamping as proving "that where a disturbance of spatial relationships is no longer possible, no heat can be produced by percussion, either."[284] In the end, he assimilated his understanding of the production and propagation of heat to the conceptual scheme of conflicting fundamental forces:[285]

281. Ørsted 1812, 283 = 1920, *2*, 162. *Identificiren* appears to be used here in the etymological sense of 'making identical.'

282. Ørsted 1812, 152–155, 164–165 = 1920, *2*, 104–106, 110–111; cf. 1813, 143–155. Only in the French version did he here speak in terms of "résistance" (1813, 145–146; cf. 1812, 153–154 = 1920, *2*, 105), though later he wrote that "[i]nsofar as the propagation of this action encounters resistance [*Widerstand*], a more or less lasting internal difference will also arise" (1812, 162–263 = 1920, *2*, 153).

283. Ørsted 1812, 167 = 1920, *2*, 111; cf. 1813, 162–163.

284. Ørsted 1812, 169 = 1920, *2*, 112. In arguing earlier against the idea that electrically produced heat is due to a mechanical disturbance, he cited the heat produced when electricity passes through fluids, since not only is the agitation there not great, but—in any event—"fluids yield no heat through mechanical agitation" (1812, 163 = 1920, *2*, 109; cf. 1813, 153–154).

285. Ørsted 1812, 172–173 = 1920, *2*, 113–114.

> The production of heat through percussion and friction serves not only to confirm our view, however, but it also teaches us what an immeasurable quantity of opposing forces lies dormant in every body. We can divide a body as much as we want, we can divest it of however much heat we can, *the capacity to obtain and conduct electricity through induction* [Vertheilung], *to produce heat through friction, percussion, and pressure, is as inexhaustible as corporeality itself.* But if we accept this inexhaustibility of forces with the generality already demonstrated in the foregoing by both chemical and electrical means, then we feel even more strongly the conviction *that these forces really do constitute the fundamental forces of corporeal nature.*

Thus, again, there is no transformation of motion into heat; rather, heat is the manifestation of an externally caused disturbance in the equilibrium of forces ever present in inexhaustible amounts in every body.

Ørsted's treatment of light brought him as close as he ever got here to suggesting something like a transformation of one "action" into another. When a heated body begins to glow, we say that "heat here goes over into light;" when an illuminated opaque body gets warmer, we say that "[*w*]*here light, as light, disappears, there heat arises.*"[286] Nevertheless, he cautioned his readers against concluding that heat and light are somehow identical: "The transition [*Uebergang*] of heat into light or of light into heat is thus not to be denied, but rather regarded as a grand fact. But we wish thereby—as is already clear from what has gone before—by no means to maintain that light and heat are the same, or even only different in degree: this would agree only poorly with experience; but we infer therefrom only the sameness [*Gleichheit*] of the forces that produce them, and regard them as different forms of action of those same [forces]."[287] This "sameness of the forces that produce them" is further evidenced by the experiments performed by Herschel, Ritter, and others on the opposing chemical actions of the two ends of the solar spectrum.[288] Like electricity, the propagation of light takes place by means of "dynamical undulations."[289] Having ignored radiant heat in the original German version of his book, he brought it, too, into the dynamical fold the next year in the French reworking of the text.[290]

286. Ørsted 1812, 212–213, 213 = 1920, 2, 131, 132; cf. 1813, 201–202.

287. Ørsted 1812, 214 = 1920, 2, 132; cf. 1813, 203.

288. Ørsted 1812, 215–217, on 215 = 1920, 2, 132–133, on 132. For Ritter's interpretation of the polar nature of light and its chemical connections, see Caneva 1997, 44–47.

289. Ørsted 1812, 222 = 1920, 2, 136, where he cited Schelling's *World soul.* On Ørsted's relationship to Schelling here, see Gower 1973, 318–319 and Caneva 1997, 52.

290. Ørsted 1813, 209–211. In a curious footnote, Ørsted again suggested to his French readers a more matter-like conception of (in this case) light and heat than he had presented to his German readers: "One sees that our theory supposes that light and heat are not propagated across an absolutely empty space. If we admitted the contrary we would, at the same time, have to consider light and heat as material substances composed of two opposing principles capable of being put in motion" (211).

Turning to magnetism, Ørsted recalled that people have long noted striking similarities between the modes of action of the attractive and repulsive forces of magnetism and those of electricity, though a "great difficulty" remains regarding the circumstance "that electrified and magnetized bodies do not act upon each other attractively or repulsively by means of their state."[291] Nor does the electroscopic state appear to exert any influence on the chemical activity of the pile: "It thus appears that the forces under different forms of action can cross or meet each other without disturbing each other. The form of action in the galvanic chain stands in the middle between the purely electrical and the magnetic, in that the forces in it are much more bound than in the former and much less than in the latter. It is thus not improbable that the electrical forces, too, can even more easily cross or encounter the magnetic [forces] without disturbance."[292]

After then exhibiting many additional phenomena that suggest the *Gleichheit* of the forces in magnetism and electricity through the similarities in their actions, he added, in words he and others would often cite after 1820: "At the same time one should investigate whether one cannot, in one of the states in which the electricity is very bound, produce any effect on the magnet as magnet"—reasoning, it would seem, that the relatively highly bound forces of magnetism would only show the effect of a state of electricity that was itself highly bound.[293] Ørsted did not indicate just what states he imagined electricity to be the most bound in; his earlier treatment of the heat generated (or not) when electricity passes with greater or less ease through different conductors did not broach the question of the possibly differing degrees of *Gebundenheit* of the electrical forces. The mode of interaction he envisioned had one form of action of the fundamental forces stimulating a body to manifest another form of action of those same fundamental forces. Electricity is not converted into magnetism: whatever identity exists between the two is solely in terms of their mutual dependency on the same opposing pair of fundamental forces, the same forces that constitute matter.[294]

291. Ørsted 1812, 247 = 1920, *2*, 146.

292. Ørsted 1812, 248 = 1920, *2*, 147; cf. Gower 1973, 346. The last sentence of the corresponding French passage (which renders *gebunden* as *latente*) reads: "It is thus probable that the electrical forces will, on crossing them, exercise a lesser influence on the magnetic forces than on the galvanic forces" (1813, 236).

293. Ørsted 1812, 251 = 1920, *2*, 148; quoted with some change in wording in Ørsted 1821b, 201 = 1920, *2*, 224. Cf. Ørsted 1813, 238, which speaks of electricity "in its most latent state;" Ørsted quoted this passage in 1821c, 162; 1821d, 4; 1821e, 322.

294. In a later section Ørsted pictured the opposition (or antithesis, *Gegensatz*) represented by the opposing fundamental forces as being part of an indefinitely extended series of *Gegensätze* such that "[t]his differing depth of the *Gegensätze* may perhaps give us the best explanation of some of the unequal degrees of [chemical] combination" (1812, 263 = 1920, *2*, 153–154).

We encounter the same views in the paragraph with which Ørsted opened a recapitulation omitted from the French version of the text, entitled "General reflections on the two fundamental forces":[295]

> In our investigations up to now it has been shown that the two forces, which we first established under the names of force of combustibility and force of comburence, are distributed over all of nature and that all of the actions that we have so far been in a position to investigate and to bring under laws are to be regarded as different forms of action of these forces. And this is so not only in chemical, but also in mechanical regard, in that we likewise perceive that even for the filling of space nothing more than these forces is necessary.

But in trying to clarify the difference between his views and the conventional dynamical view of forces he took his speculations onto previously untrodden ground by referring to the fundamental forces as "two opposing aspects of a single space-filling activity [*Thätigkeit*]" and by asking the reader to imagine a single primordial force—an *Urkraft*, in the singular—permeating all space "of which our two forces are only different forms of action," or, as he also put it, different "forms of activity" (*Thätigkeitsformen*) that are never extinguished (*nie verlöschen*).[296] The dynamism to which he, too, subscribed "allows the whole to develop together with its parts as different forms of a primordial force."[297]

He concluded with an appeal to God: "And thus we see all of nature united in one as the *manifestation* [Erscheinung] of an infinite force and an infinite reason, as the *revelation of God*."[298] Wilson interpreted this and other passages as implying that for Ørsted the primordial force *is* God:[299]

> In the end, Ørsted's *Urkraft* was nothing other than an aspect of God manifested in nature, *i.e.*, of God's creative Will, which, in turn, is organized by a second aspect of God's being, *i.e.*, of divine reason manifested in nature as the universal laws of the universe. Indeed, in much the same vein as Herder, for whom God was the "primordial force of all forces," and Ritter, who shortly before his death wrote that one "should not hesitate for a moment to call the active principle in force God," Ørsted also believed that all of nature was nothing but the evolutionary and temporal actualization of God.

For the rest, that primordial force, akin to the Divine in being the

295. Ørsted 1812, 252 = 1920, 2, 149.
296. Ørsted 1812, 257, 258, 259 = 1920, 2, 151, 151, 152.
297. Ørsted 1812, 267 = 1920, 2, 155; translation adapted from Wilson 1998, l.
298. Ørsted 1812, 270 = 1920, 2, 157,
299. Wilson 1998, lii–liii; cf. liii, where he wrote that, for Ørsted, "electricity and magnetism are ultimately identical, being only modifications of the universal *Urkraft*, *i.e.*, of God." On Ørsted, Ritter, and (especially) Johann Gottfried Herder (1744–1803) see also Wilson 1993, 598–602.

inexhaustible source of all activity in the world and thus also the ultimate ground of nature's fundamental forces, played no direct role in Ørsted's physical science. Despite his penchant for speculation, Ørsted made a consistent effort to assign to philosophy those metaphysical questions of essence and origin that lie outside the purview of empirical science.

The search for a consistent mode of representation

With a few subtle terminological changes, the general ideas concerning the forces and forms of action of nature that Ørsted elaborated between 1803 and 1813 continued to characterize his writings for another decade. At the most basic level, it is the universal forces of nature (*de almindelige Naturkræfter*) that underlie both the phenomena of electricity, magnetism, light, heat, and chemical combination *and* the basic properties of substances (extension, shape, impenetrability, force of attraction, force of cohesion, divisibility, mobility, and motility): like the former, the latter are "distinctive manifestations of the universal forces of nature."[300] Electricity, magnetism, light, heat, and chemical combination are the internal actions (or effects, *indvortes Virkninger*) of the same universal forces. Here, as in general in works published between 1816 and 1823, Ørsted preferred to speak not in terms of the fundamental forces (*Grundkræfter*) of nature, as had been his regular practice from 1798 till at least 1813, but of the universal forces of nature, perhaps reflecting a desire to emphasize the empirical over the metaphysical aspects of force; in one notable exception, from 1821, he was explicitly recalling the views he held in 1812.[301] Without abandoning his earlier practice of speaking regularly of the electrical and magnetic *actions*, he tended now more and more to speak of the electrical and magnetic force or (more usually) *forces*.[302] And, without

300. Ørsted 1817(1818), 9 (= 1920, *2*, 438–439, on 439) ~ 1817(1823), xxxv; 1820a, 25 (for the relationship of the properties of substances to the universal forces of nature). For more specific pronouncements regarding electrical actions (or forces), see also 1816, 12 (= 1920, *2*, 433) ~ 1816(1823), xvi; 1820a, 6, 24; 1821b, 200–201 = 1920, *2*, 224; for the statement that magnetic actions (*magnetiske Virkninger*) are produced by the same two universal forces of nature as the electrical actions, see 1821a, 12 = 1920, *2*, 447; 1822a, 46 = 1920, *3*, 325; for the statement that heat is produced by the action of those same forces, see 1820a, 25; for the statement that the chemical forces are the same as the universal forces of nature, see 1816, 12 (= 1920, *2*, 433) ~ 1816(1823), xvi.

301. Ørsted 1817(1818), 10 (= 1920, *2*, 439) ~ 1817(1823), xxxv; 1821a, 12 = 1920, *2*, 447.

302. Ørsted 1817(1818), 10 (= 1920, *2*, 439) ~ 1817 (1823), xxxv; 1820a, 3, 6, 24; 1820b, [2] = 1920, *2*, 216 (*vis electricæ*); 1821a, 12–14 = 1920, *2*, 447– 448; 1821b, 203 = 1920, *2*, 225; 1822a, 22 = 1920, *3*, 312. In a letter of 10 Dec 1821 to the king, he called magnetism a *Naturvirkning* (quoted in Meyer 1920b, xxxvi). In reflecting on the considerations that had led him to expect an interaction between magnetism and electricity, he wrote: "Since I had already long regarded the forces that manifest themselves [*sich äussern*] in electricity as the universal forces of nature [*die allgemeinen Naturkräfte; les* (bzw. *des*) *forces générales de la nature*], I also had to

ever establishing itself as the favored term, *activity* (*Virksomhed, Wirksamkeit*) came into occasional use as well.[303] Ørsted never succeeded either in settling upon a fixed and coherent terminology or in clearly defining the fundamental concepts that might be captured by consistently deployed terms.

Apart from electricity, Østed used force-based terminology most prevalently with regard to the chemical forces responsible for the observed combinations and dissociations of chemical substances. Combustible (*brændbare*) bodies contain an excess of the same force as in positive electricity, comburent (*ildnærende*, i.e., 'fire-nourishing') bodies an excess of the same force as in negative electricity; the uniting (*Forening*, an increasingly common term) of these two chemical forces produces heat and light. What he also termed *Brændkraft* and *ildnærende Kraft* also predominate in alkalis and acids, respectively; since these two forces neutralize each other's action, we call them opposing forces (*modsatte Kræfter*, another term now more frequently used).[304]

This mode of heat production also underlay the production of heat by friction and percussion. It was well known that friction can produce electricity in certain bodies; in Ørsted's conception, when this friction produces more electricity than can readily be conducted away, the body becomes warm. Similarly, the striking of fire with steel and stone and (somehow also) the production of heat when a nail is hammered show that percussion produces a violent electrical action (or effect, *Virkning*).[305] In the context of having explained the production of heat by electricity in terms of the disturbance of the opposing forces present in all bodies, he declared that "[t]he production of heat by percussion and friction is here easily understood, since all percussion and all friction produce the two opposing electricities that are combined together [in the body's normal state], and disturb the equilibrium in the rest of the body when they are not conducted away."[306]

Although Ørsted consistently sought to identify the ways in which the different forces and actions of nature give rise to each other, as being all manifestations of the same two opposing forces, in fact his treatment of electricity,

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derive the magnetic actions from them. I therefore expressed the suspicion that the electric forces, in one of the states in which they are very bound, could produce some effect on the magnet as magnet" (1821b, 200–201 [= 1920, 2, 224] ~ 1821c, 162 ~ 1821d, 4 ~ 1821e, 322). In the original passage (1812, 251 = 1920, 2, 148; quoted at note 293), which Ørsted himself cited, he spoke not of "electric forces" but simply of "electricity."

303. Ørsted 1820a, 21, 31; 1821a, 13 = 1920, 2, 448.

304. Ørsted 1816, 13 (= 1920, 2, 434) ~ 1816(1823), xvii; 1820a, 19–21, 31. He spoke of "the opposing forces that are found in all bodies" (1822a, 22 = 1920, 3, 312).

305. Ørsted 1820a, 28. He argued against the assumption of a *Varmestof* on the familiar grounds that it would have to be present in bodies in infinite amounts in order to account for the indefinite amount of heat that can be generated through friction.

306. Ørsted 1822a, 22 = 1920, 3, 312.

magnetism, and chemical action was notably different from that accorded heat and light: the former were much more easily interpretable in terms of pairs of opposing forces than the latter, even if light and heat were regularly treated as being produced by the uniting of either electrical or chemical forces—most notably, perhaps, from a theoretical standpoint, by means of the passage of an electric discharge through a solid body.

When the two opposing electric forces are united with very little resistance (*Modstand*), the only effect observed is that they neutralize each other (*ophæve hinanden*); as the resistance increases, the body becomes warm, then glows, then produces light.[307] Heat and light are thus related to each other in terms of relative intensity: light is produced by an intensification of the activity that produces heat (or, as he also put it, by an increase in the quantity and strength of the forces that produce heat); "[c]onversely, light can be toned down [*nedstemmes*] into heat" when the light that strikes nontransparent bodies produces heat in them.[308] Nevertheless, as before, Ørsted cautioned against concluding that heat and light are identical: "At the same time it would obviously conflict with the evidence of experience if one wished to regard light merely as strong heat, or heat as weak light. There must be something in the mode of action of the producing forces that is the cause of this difference, and this probably lies in the greater *speed* [Hastighed] with which the actions take place in the production of light."[309] He appealed to the newly available example of electromagnetism, in which the manifestly active electric forces cannot be detected with an electrometer, to argue in general that the uniting of opposing forces does not necessarily entail their complete mutual annihilation and hence that there is good reason for regarding heat and light as also being produced by the interaction of the same two forces that produce the electrical phenomena.[310] In other words, the implied objection—that if the

307. Ørsted 1816, 12–13 (= 1920, *2*, 433–434) ~ 1816(1823), xvi–xvii; 1820a, 26, 31; 1822a, 22 = 1920, *3*, 312. In 1821 Ørsted announced his intention "to give a new development to the opinion I already expressed many years ago on the production of light and heat by the *conflict* of the electrical forces" (1821c, 180 ~ 1821d, 29 [no italics] ~ 1821e, 337).

308. Ørsted 1820a, 31; cf. 1822a, 24 = 1920, *3*, 313.

309. Ørsted 1820a, 32. Note the change of expression from the earlier *Virkningsform* to the *Virkningsmaade* of this passage.

310. Ørsted 1821a, 19 = 1920, *2*, 452: "The author points out, finally, that the theory of heat and light that he already set forth publicly long ago assumes that these two great actions should be produced by the interaction [*Vexelvirkningen*] of the same two forces that produce the electrical phenomena. It has seemed inconceivable to many physicists that these forces should be united without completely annihilating each other's action. Electromagnetism, on the contrary, shows us an example of an activity produced by the same two forces that produce electricity, but under circumstances where they are united in such a way that no electrometer discovers their existence. Heat and light are produced by the same forces and by the same procedure as electromagnetism; only there is required for that a greater quantity of active forces [*virkende Kræfter*] and a greater rapidity in the latter's interaction. Only there, when the conductor has acquired so much electricity that it can conduct it away only very insufficiently, is heat produced."

electrical forces unite in a wire there cannot be any activity left over to manifest itself as heat or light—falls away in the face of electromagnetic action.

Ørsted retained the imagery from earlier publications of the undulatory propagation of electricity (1806), light (1812), and radiant heat (1813) in terms of a succession of disturbances and reestablishments of the equilibrium of the opposing forces that lie bound and hence undetected in all bodies and (inferentially, at least) in space. The phenomenon of charging by induction (*Fordelning, Vertheilung*) indicates that all bodies contain both positive and negative electricities, only bound and restrained by each other.[311] In sketching the conceptual background to his discovery of electromagnetic action, he recalled his earlier view "that electrical conduction consists in a continuous disturbance and reestablishment of equilibrium, and thus contains an abundance of activity that one does not suspect from the view of [electric conduction as] a mere flowing [*eines blosen Durchströmens*]."[312] Electrical conduction thus represents a conflict (*Wechselkampf, Conflictus, conflit électrique*) between the two opposing forces.[313] Similarly, "the propagation of light must

311. Ørsted 1820a, 6–7. Referring to his 1812 book, he recalled that he had there concluded "that magnetism must be produced by the electric forces in their most bound state" (1821a, 12 = 1920, 2, 447). For the rest, he did not develop the vague notion of 'boundness' into either a regularly deployed or analytically useful concept.

312. Ørsted 1821b, 199 = 1920, 2, 223; cf. 1821c, 161 (~ 1821d, 3 ~ 1821e, 321), which speaks of "la propagation de l'électricité" and of "un courant uniforme."

313. It is thus especially inappropriate that the English translation of Ørsted's 1820 paper rendered the *conflictus electricus* of the title as "current of electricity." What he called the "cursus virium electricarum in filo conjungente" (1820b, [4] = 1920, 2, 218) referred to the oppositely directed circular paths of positive and negative electricity *around* the connecting wire. It seems that Ørsted's belief that forces can neutralize each other's action without ceasing to exist as (potentially) active forces—as, for example, when the discharge of electricity through a good conductor produces no heat—played a significant role in his conviction that the electrical forces should somehow—perhaps in their most bound state—exert an action on magnets "as magnets." He thus continued his sketch of the train of thinking that led him to his great discovery: "I...found myself, especially in my investigations on the heat produced by electrical discharge, led to show that the two opposing electrical forces in the conductor heated through their action have, to be sure, been united, but they have not been joined [*verbunden*] in complete rest, so that they are still capable of manifesting great activity, only under an entirely different form [*forme d'action*, in the French versions] from that which one can properly call the electrical. Despite my efforts to justify the idea, one has mostly found very improbable this complete neutralization [*Aufhebung*] of forces in electrometric regard whereby in other connections a very great activity should still take place" (1821b, 199–200 = 1920, 2, 223; cf. 1821c, 161–162 ~ 1821d, 3–4 ~ 1821e, 321). It was on this idea that he ventured to build his theory of heat and light, "and thus to attribute to the apparently neutralized forces a radiation to the greatest distances" (1821b, 200 = 1920, 2, 224; cf. 1821c, 162 ~ 1821d, 4 ~ 1821e, 322). The German text's "eine Ausstrahlung in die weitesten Entfernungen" is less clear than the French text's "une action rayonnante capable de pénétrer dans les [*bzw.* jusqu'aux] plus grandes distances." His further remark—"I still remember that, illogically [*inconsequent*] enough, I expected the contemplated effect especially from the discharge of a large electric battery" (1821b, 201 = 1920, 2, 224; cf. 1821c, 162–163

be regarded as a disturbance and reestablishment of the equilibrium between the two opposing forces in space," a kind of undulation. Nevertheless, he emphasized that this succession is not one of alternating compressions and rarifactions but rather a series of decompositions and combinations (of precisely *what* he did not say), such that the undulations take place "not mechanically but chemically," that is, in terms of forces.[314] Finally, radiant heat, too, can be conceived of as "a series of successive oppositions [*Modsætninger*]," heat rays differing from light rays in terms of the latter's greater rapidity (*Hurtighed*).[315] The old ambiguity continued to attach to the ontological status of these undulations, as to that of Ørsted's forces and actions in general. In his epoch-making electromagnetism paper of 1820 he wrote indecisively of the *vis vel materia electrica*,[316] and in a major paper the next year in which he explored the conceptual ramifications of his discovery he took refuge behind the phenomenological positivism common among French scientists of the day: "I repeat here...that by *electric forces* I understand nothing but the unknown cause of the electrical phenomena, may it be bound to a free material substance [*Materie*] or even be an independent activity [*selbstständige Thätigkeit*]."[317]

After 1820 Ørsted faced the task of assimilating electromagnetism into his schema of forces and actions. For the most part he had by then given up his earlier attempts at constructing an architectonic of forces and actions, and his initial interest lay in identifying its similarities and differences vis-à-vis the others. Noting that the soon-to-be-named electromagnetic activity seems

["inconséquemment"]; 1821d, 5 ["mal à propos"]; 1821e, 322)—indicates that it was not the *logic* of his conception of the interrelationship among the forces and actions of nature that led him to perform his successful trial with the conducting wire of a galvanic pile.

314. Ørsted 1821a, 20 = 1920, *2*, 453.

315. Ørsted 1822a, 23–24 = 1920, *3*, 312–313. The context of the passage—along with the views he expressed elsewhere—makes clear what Ørsted appears to have misstated: "Varmestraalerne ere ikke forskjellige fra Lysstraalerne uden ved en större Hurtighed" (24 *bzw.* 313).

316. Ørsted 1820b, [4] = 1920, *2*, 218. Note that the regularly reprinted English translation from 1820 has (for example) "negative electricity" where the original had "vim vel materiam negative electricam" (1820c, 276).

317. Ørsted 1821b, 203 = 1920, *2*, 225. The French versions contrast "une matière imperceptible" to "une activité indépendente" (1821c, 164 ~ 1821d, 6; cf. 1821e, 323). On French positivism see Caneva 1980, 124–125, 129, 135, n. 38; 1993, 185. That Ørsted's own leanings were then rather toward the antimaterialistic side is strongly suggested by a comment in a letter to him of 21 Mar 1822 from Paris by former student Henrik Gerner Schmidten (1799–1831): "Of all the scholars [*lærde*] here I believe that Arago and Ampère are those who most love and seek truth for its own worth. One thing that's a rarity here is that they aren't materialists, and I believe that it is they who best know how to appreciate your beautiful ideas, which aim at bringing unity into the chemical and electrical phenomena, plus those of light and heat" (M. Ørsted 1870, *2*, 23–24). Note again the separate grouping of light and heat.

capable of passing unaffected through all interposed substances except iron, he remarked on its correspondence in this regard to magnetism and its difference from all of the other activities capable of being called forth experimentally—he hamed here electricity, galvanism, light, and heat—and he compared it with gravity, which penetrates everything "but which we can as little produce as strengthen or weaken."[318] The electromagnetic action itself he interpreted as a spiraling motion of the magnetic actions (or magnetic forces) along and around the conducting wire, within which the electrical forces likewise move along a spiral path. The unpublished summary of a paper he had read at the Academy sometime before indicates even more clearly the direction his speculations were taking. He was beginning to superimpose the language of motions onto that of forces and actions:[319]

> Professor Ørsted read a paper on the relationship of the electrical conflict to magnetism, light, and heat. The author sought in this paper to show that the attractive and repulsive actions that galvanic conductors exert toward each other may be explained by the spiral motions of the electrical forces, and that these spiral motions can be explained by the mode of propagation of the electrical forces....He further sought to show that the state in which electrical conduction goes over into the action of heat is accompanied by a radiation in spirals from every point of the conductor. Finally he also concluded that the action of light is the same as [the] action of heat with greater speed, thus with spiral turns of lesser separation. From this he then derived the explanation of the polarity of light, of colors, and of the relationship of light to thin plates.

For the time being, those motions existed in the limbo of Ørsted's ill-defined ontological space, where it was unclear whether one was dealing with disturbances of forces in space or modifications of some material substance. By the end of the decade he would explicitly adopt the language of a space-filling aether.

In the meantime, however, he interpreted these new relationships by invoking an echo of his earlier notion of form of action (*Wirkungsform*): "What we here a moment ago called electricity is not so in the word's stricter

318. Ørsted 1821a, 13 = 1920, 2, 448.

319. Danske Videnskabernes Selskab 1813–22(MS), entry no. 2547, meeting of 6 Apr 1821: "Professor Ørsted forelæste en Afhandling om den electriske Vexelkamps Forhold til Magnetisme, Lys og Varme. Forf. sögte i denne Afhandling at vise at de Tiltræknings- og Frastödningsvirkninger, som de galvaniske Ledere udöver mod hinanden, maa forklares af de electriske Kræfters Spiralbevægelser, og at disse Spiralbevægelser lade sig forklare af de electriske Kræfters Udbredelsesmaade....Fremdeles sögte han at vis[e] at den Tilstand, hvori den electriske Ladning gaaer over til Varmevirkning, er ledsaget med en Udstra[a]lning i Spiralen fra ethvert Punkt af Lederen. Endeligen slutter han ogsaa at Lysvirkningen er liig Varmevirkning med större Hastighed, altsaa med Spiralomgange af mindre Afstand. Heraf udledte han da Forklaringen af Lysets Polaritet, af Farverne og af Lysets Forhold til tynde Lameller."

meaning; for the force that in the open galvanic or electric circuit acted in a distinctive manner—under a distinctive form—that we call the electric or galvanic, acts here under an entirely different form that we most appropriately call the magnetic: meanwhile, since magnetism acts under the form of a straight line—that is, the opposing forces separate themselves in precisely opposite directions—[while] the forces here, on the contrary, flow incessantly into each other and form a circular course [*Kredslöb*], the author has called the action dealt with here *electromagnetism*."[320] Thus it appears here that for Ørsted the principal need for a new term stemmed from the unprecedented *form* of the electromagnetic action and not so much from the fact that it represented an interaction *between* electricity and magnetism.

The more widely disseminated and appreciably expanded German and French essays containing Ørsted's reflections on electromagnetism lend some support to this inference. In French, he argued that the two opposing electrical forces active in the discharge that heats a body through which it passes "are there so confounded that they escape all observation, without, however, having come to a complete rest, in such a way that they will still be able to display a great activity, albeit under a form of action entirely different from what one can properly call electrical."[321] In a passage garbled in the original German, he assimilated the new electromagnetic form of action symbolically to the traditional opposing-forces model of positive and negative electricity (as of north and south magnetism): "[For the sake of brevity we will designate positive electricity by +E, negative by –E, and when these forces] in a circular course no longer act upon the electrometer, and in general have assumed an entirely different form of action, then in this new form of action, by way of distinction, we want to call them +ε and –ε.[322] His extensive verbal descriptions and pictorial diagrams of the various modes of interaction between magnetic needle and galvanic connecting wire are all representations of the peculiarly circular "form of action" of the newly revealed electromagnetic forces. In that regard they merely amplify the compressed description he gave in his Latin announcement of 1820. In an account of his electromagnetic researches written in 1827, Ørsted presented his principal discovery as "the fundamental law of electromagnetism, viz. *that the magnetic effect of the electrical current has a circular motion round it*."[323]

320. Ørsted 1821a, 14 = 1920, *2*, 448.

321. Ørsted 1821c, 162 ~ 1821d, 3–4 ~ 1821e, 321; cf. the passage from the German text quoted in note 313.

322. Ørsted 1821b, 205 = 1920, *2*, 227. The words in brackets were reconstructed by the editor in accordance with the English and French versions of the text. irregularities remain in the wording as originally published, but not such as affect what is significant about it here.

323. Ørsted 1827(1830), 575 = 1920, *2*, 358.

The very different French version of the just-quoted passage reveals yet another nuance of Ørsted's understanding of electromagnetism: "For the sake of brevity we will designate the electric force one calls positive by +E and negative by –E; but while these forces have entered into the new state where they have no action [*action*] on the electrometer, but do act on the magnetic needle, we will call them electromagnetic forces and designate them by the Greek letters +ε and –ε."[324] Electromagnetism thus properly refers to the distinctive *state* of the galvanic connecting wire. That is the way Ørsted continued to use the term in both versions of this essay. Against the theory of transversal magnetism proposed by Austrian chemist Johann Joseph Prechtl (1778–1854), which explained electromagnetic action in terms of the placement of end-to-end loops of small magnets around the circumference of the connecting wire, Ørsted said he "preferred to retain the name electromagnetism for the state of the electrically traversed conductor" because nowhere in such a conductor does a magnetic pole appear and because "the continual production of new electricity in the galvanic apparatus requires that we also assume a renewed electromagnetism, an uninterrupted circular course [*Kreislauf, circulation*] of electrical forces in the conductor under the magnetic form of action. Only where the circular course is interrupted without the cessation of the opposing directions of activity does actual magnetism arise."[325]

The proper magnetic form of action thus does not form a closed "circular course," but rather a line with distinct and externally detectable poles. Magnetism, moreover, appears to preserve its state in a static fashion, whereas the electromagnetic state is continually regenerated as a result of the continual discharging and recharging assumed to take place in the closed galvanic apparatus. As he later recapitulated,[326]

> Since new electricity is continually developed in the galvanic column, the discharges must be regarded as a continually renewed give and take. The particular state of the forces that takes place in the discharged conductor, in which they act as electromagnetic forces, thus appears to me to be a continually agitated [state]. But in the magnet the same forces appear to differ from the electromagnetic form of action only to the extent that they find themselves in an almost resting state and form no closed circle. Here it is necessary to change the denomination of +ε to +m and that of –ε to –m.

If Ørsted's central interest was indeed in identifying the form or mode of action of the newly detected electromagnetic state in which the universal

324. Ørsted 1821c, 165 ~ 1821d, 8 ~ 1821e, 324.

325. Ørsted 1821b, 211 (= 1920, 2, 232) ~ 1821c, 169 ~ 1821d, 14 ~ 1821e, 327.

326. Ørsted 1821b, 219–220 (= 1920, 2, 237) ~ 1821c, 173 ~ 1821d, 19 ~ 1821e, 331. In the last sentence I have replaced the German version's rather obscure "Hier ist sodann das +ε als +*m*, das –ε als –*m* zu trennen" with a translation of the French versions' much clearer wording.

opposing forces of nature manifest their activity in the connecting wire of a galvanic circuit, and in assimilating this form of action to the (never fully formalized) conceptual scheme he had worked to develop over the previous two decades, then we must reconsider what we mean by saying that 'Ørsted discovered electromagnetism.' He did indeed discover that a magnetic needle is deflected by some action present in the connecting wire, but that was not the most significant discovery for *him*. And if we recall that Ørsted rejected the concept of an electric current as a simple flowing of electricity, then we can appreciate all the more how, for him, what he did *not* discover was the effect of an electric current on magnetism. What interested him was how the peculiar behavior of a magnetic needle suspended in the vicinity of a connecting wire reveals the existence and the peculiar closed-circular form of the opposing electromagnetic forces aroused into action by the continual discharging and recharging of the galvanic column. The misconstrual of the nature of Ørsted's discovery is analogous to the cases of Ritter's 'discovery of ultraviolet light' and Seebeck's 'discovery of thermoelectricity:' in each case what the discoverer thought he was principally discovering was decidedly *not* what historical convention has identified it to be.[327] In each case the basic *phenomena* in question are relatively simple and ostensibly unproblematic, but in every case the *meaning* of those phenomena is precisely what was at issue, and in every case their meaning for their discoverer was very different from the canonized characterizations that have come down to us.

The one remaining significant issue that continued to guide Ørsted's thinking was his abiding division of physics (as *almindelige Naturlære*) into *Bevægelseslære*, dealing with the external changes of bodies, and *Kraftlære*, or chemistry, dealing with their internal changes.[328] Chemistry thus embraces everything that does not belong to the theory of motion—in particular, the theories of light, heat, electricity, and magnetism. As usual, he noted the possibility of a third division of physics, dealing with the uniting (*Forening*) of forces and motion—as, for example, in light and radiant heat—but he could not decide whether it should comprise a separate division or be included under the theory of force.[329] But for a subtle but important nuance in the wording, this was essentially the position he advanced in his textbook of 1844, *The*

327. Caneva 1997, 44–47, 58–59, 76.

328. Ørsted 1817(1818), 9–10 (= 1920, *2*, 438–439) ~ 1817(1823), xxxv; 1822a, 24–25 = 1920, *3*, 313.

329. In an essay from the mid 1840s, after noting the unity discovered during the nineteenth century among the "chemical" actions of heat, light, electricity, and magnetism—a unity nevertheless less complete than that of the laws of motion—Ørsted held out the prospect of a future time "in which the chemical and mechanical laws of nature will be united into a more intimately connected knowledge" (1845/46[1850], 141 ~ 1846[1847]a, 73; the latter omits the former's "more").

mechanical part of physics, as in its posthumously published German translation of 1851, which a long-time friend and former student had prepared in close collaboration with him:[330]

> The universal science of nature treats of either what are for bodies purely *external changes*, which consist in change of place and position, i.e., *motion*, or the *internal* [changes], in which no motion immediately perceptible to the senses appears, and which are called *chemical* changes, the word taken in its most inclusive meaning. The universal science of nature is thus divided into *theory of motion* and *chemistry*. The latter has also been called *theory of force* because one regards the internal changes as the nearest manifestations of the individual forces of nature; but this may better be made the object for an investigation at the conclusion of the science.

What have previously been internal *changes* of unspecified character now appear to be imperceptible *motions*. Such, too, was the understanding of chemical effects (or actions) as "probably also motions" that, nine months earlier, had marked his comments on Colding's first paper, comments in which Ørsted reasserted his long-held classificatory distinction between mechanical and chemical "forces."[331] Ørsted expressed this change of view more explicitly in the German edition he prepared of his *Spirit in nature*, whose second volume, published in 1851, incorporated an edited version of the 1822 German translation of the *First introduction* of 1811. He added a new footnote to the word "Kraftlehre" in a passage (quoted above) that noted that the theory of motion has become almost completely transformed into mathematics: "Already in the first edition of these paragraphs—and already earlier, too—I called *theory of force* all of the parts of physics that are not *pure* theory of motion; that is, the theory of the laws of chemical combinations and separations, the theory of electricity, magnetism, [and the] activity of heat and light. However much now all these actions point to internal motions, I have not hitherto wanted to change the name *theory of force*."[332] Ørsted's attachment to his dichotomous schema was thus so deeply rooted that it held up against changes in his assessment of the ontology of the phenomena that, as he realized, should rightly have caused him to rethink his original distinctions.

Ørsted's increasingly explicit acceptance of "internal motions" for the explanation of the mode of action of electricity, magnetism, heat, light, and chemical changes—note that he still lacked a general term for these agencies,

330. Ørsted 1844, 3–4; 1851a, 5. On Ørsted's role in the preparation of the German edition by L. Meyn, see 1851a, viii.

331. See Ørsted's comments of 10 Dec 1843, quoted at notes 197 and 198.

332. Ørsted 1850–51a, *2*, 464 ~ 1852, 461; *not* in 1847, 13 or 1851–52, *5*, 124. See the passage quoted at note 260.

and still tended to class heat and light together and somewhat apart from the others—made its first public appearance in 1830 in an article on thermoelectricity that he wrote in English in 1827 for David Brewster's *Edinburgh encyclopædia.* But he had not yet fully abandoned the language of "powers"—his English word for the *Kræfter, Kräfte,* and *forces* of his Danish, German, and French writings. Thus, writing in the third person, Ørsted reported that "[t]hroughout his literary career, he adhered to the opinion, that the magnetical effects are produced by the same powers as the electrical. He was not so much led to this, by the reasons commonly alleged for this opinion, as by the philosophical principle, that all phenomena are produced by the same original power."[333] Citing his German and French works of 1812 and 1813 as if they were the same, he noted that "[i]n this work, he proved that not only chemical affinities, but also heat and light are produced by the same two powers, which probably might be only two different forms of one primordial power. He stated also, that the magnetical effects were produced by the same powers."[334]

This is all vintage Ørsted, even the otherwise rather rare language of a (singular) primordial power. Indeed, most of the long essay's short concluding section, "Some theoretical considerations," remained comfortably within the world of "forms of action" and "powers," including both a singular fundamental power and pairwise opposing powers:[335]

> The question has during late years often been proposed, *whether or not magnetism and electricity are identical*....His opinion is, that all effects are produced by one fundamental power, operating in different forms of action. These different forms constitute all the dissimilarites. Thus, for instance, pressure upon the mercury of the barometer, wind and sound, are only different forms of action of the same powers. It is easy to see that this fundamental identity extends to all mechanical effects. All pressures are produced by the same powers as that of air; all communications of motion, and likewise all vibrations, owe their origin to the same expansive and attractive powers, by which each body fills its space, and has its parts confined within this space. This fundamental and universal identity of mechanical powers has for a long time been more or less clearly acknowledged; but the effects which have hitherto not been reduced to mechanical principles, seemed to be derived from powers so

333. Ørsted 1827(1830), 575 = 1920, *2*, 356.

334. Ørsted 1827(1830), 575 = 1920, *2*, 356. Perhaps because of the changing focus of his writings during the last two dozen years of his life, such pronouncements, commonplace until the early 1820s, were all but absent from the works he published after 1830. Indeed, one of the few occurrences anywhere came in an undated letter to Weiss—part of their correspondence on atomism and dynamism—sometime after May 1829: "The chemical forces appear to present themselves to us increasingly as motive [forces]. Is it not apparent that they are the same as those that produce electricity, magnetism, light, and heat?" (Harding, *2*, 330).

335. Ørsted 1827(1830), 588 = 1920, *2*, 396–397.

> different, that the one could scarcely be deduced from the other. The discoveries which began with galvanism, and which have principally illustrated our century, led us to see the common principles in all these actions.

Briefly cataloging the discoveries that demonstrated the connection between galvanism and chemical actions, the production of heat and light "by the union of the opposite electrical powers," and the generation of heat "by the electrical and chemical powers," he also noted, rather overgenerously, his own contributions:[336]

> He proved that the electrical powers are present in all cases where heat and light are generated. That magnetical effects can be produced by the same powers need not here be mentioned. As the chemical powers give rise to expansions and contractions, it appears that their nature is not different. Thus acknowledging the fundamental and universal identity of powers, effects must be considered as different, when their form of action differs, and therefore magnetism, in this acceptation of the term, is far from being identical with electricity. It would likewise be erroneous to pretend that all chemical effects are produced by electricity; but the truth seems to be, that the chemical effects are produced by the same powers which, in another form of action, produce electricity. The name of *electro-chemical* theory, given to the modern chemical theory, seems therefore less admissible than the denomination of *dynamico-chemical*, proposed by Oersted so early as 1805.

We are still in familiar territory. Only in the essay's last six sentences did Ørsted reveal his changed thinking about the underlying nature of those powers:[337]

> The dynamico-chemical theory must still remain very imperfect, until it is decided if the powers acting in magnetism, electricity, heat, light, and chemical affinities are to be ascribed to vibrating, circulating, and other internal motions or not. That these effects do not pass without the most remarkable internal motions, appears from the experiments upon light and upon electro-magnetism. The electrical current is a system of rotative motions, upon whose directions, perhaps, all the disparity of positive and negative electricity depends. It is not improbable that even magnetism involves some rotations, and thus the opinion of Mr. Ampère comes to agree with ours, at least in this point. When the transmission of the electrical current through liquid bodies is accompanied with a chemical decomposition, it seems necessary to admit that the substances styled electro-positives and electro-negatives, must rotate in opposite directions, and we may suppose that their neutralizing powers are connected with the propensities to those opposite rotations. The new discoveries, in short, reveal to us the world of secret motions, whose laws are probably analogous to those of the universe, and which deserve to be the subject of our most earnest meditations.

336. Ørsted 1827(1830), 588 = 1920, 2, 397–398.
337. Ørsted 1827(1830), 588–589 = 1920, 2, 398.

It appears that Ørsted had come to believe that the phenomena had to be explained by a diversity of hidden and (especially) rotative motions. The exemplar of such motions was, of course, the electromagnetic rotations that he had discovered.

From the late 1820s, Ørsted usually interpreted phenomena he classed as "chemical" in terms of internal motions, not forces. Thus in his correspondence with Christian Samuel Weiss on atomism and dynamism, begun in January 1829, he criticized Kantian dynamism for its inability to explain the facts of chemistry on the basis of its presumed attractive and repulsive forces. Although Ørsted accepted the general argument that matter must be somehow basically active—as, for example, when it resists penetration by other matter—and that this activity requires "something active, which we call force," he opted for what might be called an operational ontology of matters and motions that was better suited to making sense of particular phenomena.[338] "The system I defend I would call, with an expression borrowed from you yourself, the system of *articulation* [Gliederung], if I did not at the same time find myself compelled to assume an internal motion, an either circulating or oscillating [motion] of the corporeal particles, whereby the system, if it is to be adequately designated by means of a name, must be called an *entostrophadic* [system]."[339]

Ørsted began his defense of his system of internal motions and oscillations by appealing to the phenomena of light and heat, which he classed together because, as he told Weiss, he had become increasingly convinced "that light and heat are oscillatory and that heat is distinct from light only through [its] slower oscillations [*Oscillationen*]."[340] The light radiated out from one heavenly body is transformed into heat when it is absorbed by another, the smallest particles of which then send and receive heat by a process of continuous *internal* radiation ("[durch] ein unaufhörliches Hin- und Herstrahlen zwischen den Grundtheilen").[341] Thus although Ørsted believed that this action imparts motion to the smallest particles of matter, he did not conclude that this molecular motion constitutes the body's heat. What heat *does* consist in he neglected to say. Although he had long rejected the common assumption of some kind of matter of heat (*Wärmestoff*), by 1829 he had come to accept

338. Ørsted, letter of 30 Jan 1829 to Weiss, in Harding 1920, *1*, 280–285, on 282. For another identification of matter as "das Raumerfüllende," "das Thätige," see another (undated) letter to Weiss (337).

339. Ørsted, letter of 30 Jan 1829 to Weiss, in Harding 1920, *1*, 282; Ørsted's nonce coinage, "entostrophadisches," clearly derives from Greek *entos*, 'within,' and *strophē*, 'a turning.'

340. Ørsted, letter of 30 Jan 1829 to Weiss, in Harding 1920, *1*, 287; quoted in Meyer 1920a, lviii; cf. another (undated) letter to Weiss in Harding 1920, *1*, 332, where he also compared light to sound waves.

341. Ørsted, letter of 30 Jan 1829 to Weiss, in Harding 1920, *1*, 287.

an aether as the material explanation of heat and its kin:[342]

> In order that you know precisely where you are with me, I hereby expressly declare that I place the peculiarity of light, heat, electricity, and magnetism in motions. These motions, however, must necessarily often take place in matters [*Materien*] that are finer than all known to us, e.g., the matter diffused in space. One may call this matter, or perhaps better these matters, aether or kinds of aether; or whatever one wants. But I maintain that the oscillations of light—or, if you will, the articulation of light—include at every moment its wave parts, its + and –, or, as we can also say, its separated parts of space, and that their plus and minus are not present everywhere at the same time.

In moving from opposing forces to opposing motions, Ørsted was able to retain much of the conceptual baggage of oppositions (or antitheses: *Modsætninger, Gegensätze*) with the possibility that that implied not only of mutual annihilation, but of mutual creation out of zero or 'nothing.' Given the relationship of reaction to action, the creation of any motion must be accompanied by the simultaneous creation of an equal and opposite motion, and the formal identity between the conventional parallelogram of forces and parallelogram of motions entailed the possibility of the simultaneous creation of equal and opposing forces *and* motions.[343] Either way, neither forces nor motions are quantitatively conserved, except insofar as the sum of each must always be rigorously zero.

Ørsted's adoption of an aether made its public appearance in 1830. In a review of a work of Steffens', it appeared at first as if his conceptual world was still one of opposing forces going in and out of equilibrium, rather in the mode of interaction just described:[344]

> Regarding the proposition that opposites seek to unite [*at det Modsatte søger Forening*], the author says that that is, in the opinion of some, in order to reestablish a disturbed equilibrium, in the opinion of others, in order to neutralize [*ophæve*] a real opposition [*Modsætning*]. Are these assertions supposed to be anything but expressions for the same thing in two different modes of representation? If we take the word equilibrium in its broadest sense, where we can also speak of electric equilibrium, magnetic equilibrium, etc., then every departure from equilibrium is a production of oppositions, and every return to equilibrium a neutralization of oppositions. When we observe things in their activity, we may call the oppositions *counterendeavors* [Modbestræbelser], and the cooperation [*Samvirkningen*] of equal counterendeavors *equilibrium*. If we are correct in this, many disputes between philosophers of nature and physicists will fall away; for the same people who hold it to be incomprehensible when it is said

342. Ørsted, undated letter (after May 1829) to Weiss, in Harding 1920, *1*, 336.
343. Cf. Ørsted 1844, 14–19; 1851a, 19–22.
344. Ørsted 1830a, 20–21 (= 1850c, 171–172) ~ 1852, 271.

> that all oppositions in existence amount to [*gaae op i*] an identity, will not easily find any difficulty in conceding that all motive forces in the world would, united, constitute an equilibrium, the same with all magnetic forces, all chemical forces, etc. But since natural scientists have gradually become more familiar with these oppositions, and it has become clear that many differences that earlier appeared to be essentially irreconcilable [*i deres dybeste Grund uforenelige*] are only different kinds of opposition of these forces, they have thus been obliged at least to find probable that fundamental proposition which the philosophers of nature represent as certain.

Yet even as Ørsted continued to speak this language when the occasion demanded, he recorded his own conceptual translation into a world of matters, motions, and aethers:[345]

> The author adduces much against the fictitious substances *Varmestof, Lysstof, electriske Materier, magnetiske Materier*, and he promises to contest them further. But we believe that, even without so strong an opponent, they will have to leave the battlefield. That light is produced by oscillations [*Svingninger*] in a universally diffused subtle matter that we call *aether* has—as the author, with us, admits—been accorded the greatest probability by the latest investigations. But if light consists in such oscillations, so likewise must radiant heat; and we have already long had sufficient grounds to regard heat as a radiation that is only distinguished from light by slower oscillations. But the ease with which we can transform electricity into heat whenever we place obstacles in the way of its flow seems to reveal that electricity depends no less on oscillations, and that these need only be brought closer together in order to constitute oscillations of heat. This is confirmed all the more by the fact that in good conductors heat goes over into electricity, as we see in thermoelectric experiments....Magnetic actions are so inseparable from electric, and differ from them only by their direction, which stands perpendicular to the electric, that it would be exceedingly strange if one wished to assume for them a distinct matter. Everyone who is acquainted with our century's chemical–electrical investigations will easily see how much even our conceptions of chemical actions—consequently also of chemical compositions, and consequently of all bodies present in daily experience—are dependent on them [i.e., oscillations of the aether].

Ørsted re-presented these ideas a few months later in a paper read before the Academy of Sciences on the relationship among sound, light, heat, electricity, magnetism, and chemical actions. Again he argued that light and heat differ only with regard to the rapidity of their oscillations and that if light consists in oscillations of the aether (*AEthersvingninger*) then so, too, must heat. As a consequence, he argued—as he claimed to have proposed already in 1813—"that all heat is radiant heat [*Straalevarme*], and that the heat called

345. Ørsted 1830a, 36–37 (= 1850c, 186–187, reading "for dem" with the latter instead of the former's "for denne" in the next-to-the-last sentence) ~ 1852, 283–284.

conducted is only heat radiated back and forth among the fundamental particles" of matter.[346] The difference between free and bound heat is thus to be sought in terms of the greater or lesser rapidity of the internal thermal radiation. And again he argued that, if light and heat are oscillations in the aether, electricity and magnetism must also be regarded as different modes of oscillation. Noting briefly that chemical actions must also be accompanied by internal motions, he closed on a note of relative diffidence:[347]

> For the rest, he did not wish it to be regarded as completely settled that light consists in oscillations of the aether; rather he only wished to show that, by assuming the view that has gained so much in probability in recent times, the reciprocal connection between electricity, galvanism, and magnetism may be represented with the same continuity [*ligesaa uafbrudt*] as in the theory that took its starting point from electric forces—a truth that, under another form, he already pointed out in his *Views* [sic] *of the chemical laws of nature* of 1812.

In a semipopular address of 1846 on "The essential unity of the capacity for knowledge in the whole universe," Ørsted replayed his picture of light as vibrations or waves in the aether (*Zitterungen des Aethers, Zittringer i AEtheren; AEtherwellen, AEtherbølger*) and maintained that heat and light differ only with regard to the rapidity of those aether vibrations, that light rays can go over into (*übergehen in, gaae over til*) heat rays, and that even faster than light's are the oscillations (*Svingninger*) of "the invisible rays that produce certain chemical actions."[348] That is as far as he ever got to working out the details. As with his earlier imagery of different forms of action of the fundamental opposing forces, he never succeeded in giving his ideas the kind of coherence and precision that might have made them more than just vaguely explanatory or that might have suggested specific experiments capable of testing them. As Ørsted's own accounts make very clear, although he was convinced long before 1820 that electricity and magnetism are merely different manifestations of the same two fundamental forces of nature, and hence that the action of one should be able to arouse the action of the other, his own hunches with regard to the optimal conditions for such an interaction were all wrong. In that case his general conviction bore fruit while his specific ideas were barren. Here his speculations died wholly without issue.

Moreover, a typical ambiguity hung over Ørsted's concept of aether: What kind of matter or substance is it? What is its relationship to ponderable matter? Does it have weight? While others wrestled with the profound problem of defining the mechanical properties of the postulated luminiferous

346. Ørsted 1830b, 25 = 1920, 2, 481.

347. Ørsted 1830b, 26 = 1920, 2, 482.

348. Ørsted 1846(1847)a, 69, 70, 74 ~ 1845/46(1850), 136, 137, 143 ~ 1852, 100–101, 106; 1846(1847)b, 120 ("AEthersvingninger"), 121 (quote) = 1920, 2, 547–548, 549.

aether, Ørsted raised and answered no such questions. Conceptually even more confusing is the fact that, in other contexts, Ørsted never entirely abandoned the language of force or the originally Kantian idea that the very conception of matter entails the assumption of active forces—if, to be sure, he no longer stressed their pairwise opposing nature. Hence the possibility remained in the background that the aether, too, might itself ultimately be a construct of forces. In this regard, however, as often earlier, there was an appreciable difference between Ørsted the natural scientist and Ørsted the philosopher of nature.

In his Danish textbook of 1844, as in the somewhat expanded German translation of 1851, Ørsted defined matter in the usual fashion as that which fills space, which it does by offering resistance to other matter. That space-filling activity we call a (*sic*: not *the*) force of expansion.[349] Yet the familiar Kantian construction of matter out of opposing fundamental forces was absent: although matter retained some activity, that activity no longer defined its dynamic essence. Yet at the same time, in a dialog written sometime after around 1846 and prominently published as the first item in his *Spirit in nature*, Ørsted reasserted the primacy of "something active in things [*noget Virksomt i Tingene*]," an activity (*Virksomhed*) by which, for example, one stone supports another resting on top of it. When something is effected, there must be some kind of active or efficient cause (*noget Virkende*).[350] Bodies have in themselves an activity by which they fill space; indeed, bodies *are* force-filled spaces ("de ere kraftopfyldte Rum"), and thus the corporeal (*det Legemlige*) is more closely related to the spiritual (*det Aandelige*) than one usually imagines.[351] Thus in different writings and at different times Ørsted advanced what looks like a graduated ontological hierarchy, from corporeal to dynamical to spiritual to an ultimate grounding of all existence in the will of a rational God.

There is one more twist to put on the nature and scope of Ørsted's conception of force. He sometimes extended the concept of force to embrace gravitation, without assigning it a definite place in his various conceptualizations of the relationship among the "chemical" forces manifest in electricity,

349. Ørsted 1844, 5; 1851a, 9. The German edition added a gloss that suggests that Ørsted recognized the inadequacy of this conventional formula: "The definition [*Bestimmung*] given here of the distinction between a body and that which is not body, between matter and that which is not matter, is in no way supposed to exhaust these concepts; on the contrary, a series of new definitions will be added little by little, and each of these concepts will be fully exhausted only by the whole of the science." He appears not to have redeemed this promissory note.

350. Ørsted ca. 1846/50(1850), 5–6 ~ 1852, 3.

351. Ørsted ca. 1846/50(1850), 7–8 ~ 1852, 4; cf. 1845/46(1850), 125 (~ 1846[1847]a, 62 ~ 1852, 91): "Nature is not merely something corporeal, it is suffused and controlled by spirit, as appears already from its infinite lawfulness."

magnetism, heat, and light. Gravitation (*Tyngden, die Schwere*) was, however, a topic he could hardly avoid addressing in his textbooks. Noting that the gravitational attraction exerted by a body decreases with distance in accordance with the law that the actions (*Virkningerne, Wirkungen*) at different distances are inversely proportional to the square of those distances, he asserted that the same law holds not only for attraction "but for every force that acts outwards from a point in all directions."[352] If one imagines that point surrounded by concentric spherical surfaces, then the same force (*den samme Kraft, dieselbige Kraftgröße*) acts over a larger surface the farther out it goes, but more weakly, in such a way that from the simple geometry of the situation we conclude that the action of any force emanating from a point must be inversely proportional to the square of the distance.[353] In the German version, though not in the earlier Danish, Ørsted commented further on the implications of this law:[354]

> It is clear by itself—though well to remark, since false ideas often prevail here—that the force itself is not weakened by the distance, but only distributed over a larger sphere of action [*Wirkungskreis*]. Rather, one finds the magnitude of the force the same for all distances if one takes together the sum of the actions [*Wirkungssumme*] of all those parts that have the same distance from the starting point of the force.
>
> Since no force *by itself* can be extinguished or diminished—let alone increased—this law is therefore universally valid for forces that act outwards from a point in all directions throughout space. It thus also finds confirmation and application in the theories of light, heat, electricity, and magnetism.

Thus Ørsted in his own way almost enunciated a principle of the imperishability and uncreatability of force, at least for a force acting "by itself" and for forces that, like gravity, "act outwards from a point in all directions." His extension of this law of action to light, heat, electricity, and magnetism is multiply curious. For one thing, although he long devoted great attention to the problem of determining the modes of action and motion of that foursome of activities, not since his ephemeral suggestion in 1805 that the basic form of positive electricity is a radiating point had he characterized the actions or motions of any of those activities as radiating in straight lines away from a central point. Even for light and heat, whose rays follow such a course, the motions he was usually interested in were their oscillations. And the characteristic feature of the action of the electromagnetic forces was precisely their

352. Ørsted 1844, 170; 1851a, 163.

353. Ørsted 1844, 170–171; 1851a, 163–164. He elsewhere called this relationship a "prescript of reason [*Fornuftforskrift, Vernunftvorschrift*]" (1845/46[1850], 129 ~ 1846[1847]a, 64).

354. Ørsted 1851a, 164.

noncentral, rotative nature. For another thing, one wonders whether Ørsted intended to refer gravitation to motions of the aether, as he had attempted with the other activities. There is no hint that he tried. Nor did he explicitly assimilate gravitational force to the kind of conflict that he long insisted underlies not only electricity and magnetism but also, in later years as opposing motions, even light and heat. And finally, whether as forces or as motions, Ørsted long insisted on the indefinite creatability of heat, light, electricity, and magnetism, which renders meaningless any talk of extending to them the kind of constancy of action he identified with gravitation. And since their actions come in opposing pairs, one never really has with them a force acting "by itself" and hence proof against extinction or diminution. Perhaps this grasping late in his life for an understanding of a connection, even if purely formal, between gravitation and the forces of light, heat, electricity, and magnetism, coupled with a vague notion of their quantitative unchangeability, represents the extent of Ørsted's ability to respond positively to Colding's assertion of the imperishability of the forces of nature.

5. THE FORCES, LAWS, AND UNITY OF NATURE: REASON AND THE WILL OF GOD IN ØRSTED'S NATURAL PHILOSOPHY

Given the visibility of his well-known and widely translated book, *The spirit in nature* (mistranslated into English as *The soul in nature*), it is hardly surprising that commentators have long noted Ørsted's deep and abiding belief in the divinely regulated harmony that permeates all aspects of the physical and spiritual worlds—where "spiritual," in the sense of Ørsted's *aandelig* and *geistlich*, includes what we would term human intellectual capacities and attainments. As he put it succinctly in an oft-quoted passage with which he closed his address on "Fundamental features of the physics of the beautiful," delivered at the Stockholm meeting of Scandinavian scientists in 1842,[355]

> The laws of nature in the corporeal world are laws of reason, revelations of one [een] rational will; thus when we imagine all of corporeal nature as the continual work of eternal reason, our contemplation cannot stop with that, but leads us to see in our thought the laws of the universe [*Alnaturen*]. In other words,

355. Ørsted 1842(1843), 43 (= 1851–52, *3*, 169, which supplies the missing "i" in the original's "[i] vor Tænkning") ~ 1852, 384; translated in Meyer 1920a, clxv and (in part) in Dahl 1963, 176; 1972, xix. The word in the title translated as "physics"—*Naturlære*—is in some ways closer to the sense of the contemporary English term natural philosophy, though not to the *Naturphilosophie* of Ørsted's usage. On the general theme of this section, see Meyer 1920a, clxiii–clxvi; 1920b, cl–cli; Levere 1971, 138; Billeskov Jansen 1987, 31–32, 48–52; Wilson 1993, 602; 1998, xlv–xlviii. In a preface to one of the volumes of Ørsted's *Gesammelte Schriften*, Peter Ludvig Møller (1814–1865) traced these aspects of his thought to Schelling's *Identitätslehre* (1850–51b, *3*, viii).

> spirit and nature are one, seen from two different sides. We thus cease to wonder at their harmony.

As early as 1807 Ørsted was writing that our endeavors to gain insight into nature have as their goal "to bring the separated phenomena under common points of view, to discover the laws to which everything must conform, in short, to bring [the] unity of reason into nature."[356] He gave these ideas their fullest early expression in his textbook of 1809 and in the reworkings of its introductory sections in Danish and German in 1811 and 1822. At center stage was the remarkable unity (*beundringsværdig Enhed, bewundernswürdige Einheit*), the common essence (*fælles Væsen, gemeinschaftliches Wesen*) that we observe among the apparently diverse phenomena of nature.[357] Examples, briefly mentioned, from similarities among plants and animals, from the universality of the laws of motion and gravitation, and (rather obscurely) from "periods in the development of the earth, in dynamic actions, and in the motion of the magnetic needle," all illustrate for us empirically "that which philosophy strictly proves, *that every well-conducted investigation of a limited object discovers for us a part of the whole's eternal laws.*"[358] When we examine these laws more closely, we find that they are in complete accord with reason, an infinite reason that manifests itself through the "infinity of activity and forces" in nature's diversity as "the eternal being's revelation in nature," as "*the all-controlling infinite reason that pervades the universe.*"[359] It is this internal unity of nature and the correspondence between it and reason that makes natural science possible.

In the 1811 and 1822 reworkings of his text Ørsted elaborated on the "eternal laws" mentioned above, for the first time bringing in the idea of unchangeability in nature:[360]

> These laws, now, and the force by which they are carried out, are the only thing unchangeable [*det eneste Uforanderlige, das einzig Unveränderliche*] in nature. Whereas every thing [*Ting, Ding*] ceaselessly changes its position, and the substances of which it is composed ceaselessly change, the laws by which this occurs, and only these, remain constantly the same. It is also by them alone that

356. Ørsted 1807a, 15 (= 1851–52, *5*, 12) ~ 1807b, 204 (= 1920, *1*, 322) ~ 1852, 307. I translate the German version's "gemeinschaftliche Gesichtspunkte" instead of the (otherwise largely equivalent) Danish version's "fælles Benævnelser"—i.e., common designations (or denominators). The German text of 1850–51b, *3*, 154 is somewhat different.

357. Ørsted 1809, 3–4 ~ 1811, 3 (= 1920, *3*, 156–157) ~ 1822b, 460 ~ 1852, 448.

358. Ørsted 1809, 4, 5 ~ 1811, 4 (= 1920, *3*, 157) ~ 1822b, 461 ~ 1852, 449. The Danish versions have "en Deel af het Heles evige Love" where the German adds "einen Theil der ewigen Gesetze des unendlichen Ganzen."

359. Ørsted 1809, 5.

360. Ørsted 1811, 4–5 (= 1920, *3*, 157–158) ~ 1822b, 462 ~ 1852, 449–450. The German has "Wesen des Dinges" instead of "Tingenes Væsen" at the end.

> one thing is different from another; for we find the most dissimilar things composed of the same substances, and the further our investigations advance the more we are convinced that the matter in all things, as well as the forces by which life and activity are sustained in nature, are everywhere the same, but that that which gives objects their particular character and produces the infinite diversity in them is only the manner in which the actions in every thing take place, the laws of nature by which everything in them is ordered and controlled. In other words things, everywhere of the same substance, are, by means of the same forces, in a ceaseless transition from one state to another, in a constant becoming. Substance itself is nothing but the space filled by means of the fundamental forces of nature. That which gives things their unchangeable characteristics is, then, the laws by which they are produced. But that which constitutes the unchangeable as well as the distinguishing [aspect] of things can rightly be called their essence, and the part thereof that they do not have in common with others, their distinctive essence. We thus venture to stipulate *that the laws of nature by which a thing is produced, taken together, constitute its distinctiveness, and that knowledge of the laws of nature in their activity is knowledge of the essence of things.*

Ørsted made one significant change in this passage in 1822: where the Danish had only the laws of nature remaining the same, the German said that it was "the fundamental forces and their laws" that remain the same. We thus see how, for Ørsted, the characteristics—and thus also the scope and meaning—of nature's rationality, laws, and fundamental space-filling forces were intimately interconnected. In restating the identity between the laws of nature and the laws of reason, he added that the chain of natural laws can be regarded as a *Naturidee*, that "*the whole world is the expression of an infinite all-embracing idea,*" and that "*the world is only a revelation of the deity's united creative force and reason.*"[361] In remaking some of these same points, other additions to the German version stressed the role of God's will alongside His reason and strengthened the notion of the unchangeability of the laws and forces of nature as well as their intimate relationship:[362]

> All prescripts that one can give for the investigation of nature must originate from the fundamental truth *that all of nature is the revelation of an* **infinitely** *rational will, and that it is the task of science to apprehend with* **finite** *forces as much of it as possible....*
>
> *The laws of nature are unchangeable*, like the will out of which they originate.

361. Ørsted 1811, 6 (= 1920, *3*, 159) ~ 1822b, 463 (which omits the "only" from the Danish wording) ~ 1852, 451. The last phrase is quoted in translation from the German in Wilson 1993, 602.

362. Ørsted 1822b, 475, 476 (= 1920, *3*, 167, as a footnote to Ørsted 1811) ~ 1852, 454, 455.

> *The fundamental forces of nature are indestructible.*
>
> By fundamental forces we understand the simplest and most basic modes of expression [*Aeußerungsarten*] through which the creative force makes itself known in the perceptible world [*sinnliche Natur*].

Ørsted larded his book of 1812, *View of the chemical laws of nature*, with the occasional unelaborated assertion that nature's eternal laws govern a continuous process of development that produces a creation having visible unity; that the indubitable lawfulness of nature cannot but correspond to reason, the totality—the unity—of the laws themselves representing "the higher law by which [each thing] has been produced;" and that the laws of nature are the same as the laws of reason, so that "we see all of nature as the *manifestation* [Erscheinung] of an infinite force and an infinite reason united in one, as the *revelation of God.*"[363] In an essay of 1815 on "The cultivation of science considered as an exercise of religion," Ørsted asserted that both reason and experience declare that the only things constant (*bestandig*) in the corporeal world are the forces that produce things and the laws by which they act, then added: "But the forces all resolve themselves into one fundamental force manifesting itself in two opposing modes, and upon closer examination the laws show themselves to be a rationality [*Fornuft*] pervading and controlling all of nature."[364]

Ørsted revisited this general topic with renewed energy in the 1840s, notably in *The mechanical part of physics* (1844) and in a number of nontechnical writings from then until his death in 1851. We are told again and again that the laws of nature are laws of reason, a fact which explains why it has often been possible for scientists to anticipate in thought what would be found in experience; that nature is a rational whole whose development can be regarded as the unfolding of an active idea, a manifestation of the will of God; and the like.[365] We again encounter the nexus of *Virksomhed, Kraft*, and *Villie*:[366]

> But just as in all thinking there is an activity, and the thought [that is] thought without it is only a form of thinking, so is there in every existing thing an activity through which it maintains its existence and asserts it against other

363. Ørsted 1812, 65–66, 268–269, 270 = 1920, 2, 66, 156, 157, the last passage quoted in Wilson 1998, li. See 288 *bzw.* 164–165 for the statement that human beings have the real, if limited, ability to discover the lawfulness—i.e., the manifestation of reason—in nature.

364. Ørsted 1815, 101 = 1850a, 182; 1852, 136. For yet another assertion that "all laws of nature are laws of reason," see Ørsted 1830a, 40 (= 1850c, 189) ~ 1852, 286.

365. Ørsted 1844, 1–2; 1851a, 1–4 (with expanded treatment); 1846(1847)b, 118 (= 1920, 2, 546); ca. 1846/50(1850), 16, 25–26, 32 (= 1852, 11, 18–19, 23–24); ca. late 1840s (1850), 82–83, 118–121 (= 1852, 59, 87–90); 1851b, 4–8, 12, 13–15, 43–47.

366. Ørsted 1844, 2; 1851a, 1–2 (which has "Im Gebiete des Geistes" instead of "I Tænkningen" in the third sentence and "eine Mehrheit von Kräften" instead of "*Kræfter*" in the last); cf. ca.1846/50 (1850), 32 (= 1852, 23–24); 1851b, 13–15.

> things. Without this activity it has no reality. In thinking we call this active [aspect] will, in external objects force. But just as will and thought are *one*, only considered from two sides, so also force and law of nature; they are manifestations [or expressions: *Yttringer, Aeußerungen*] of divine will and divine thought. *Force* in nature is, to be sure, one, but in its activity, after the manifold forms of thought that manifest themselves in nature, it is apprehended as *forces*.

In all this talk of force and forces, Ørsted continued to speak of the actions (*Virkninger*) of electricity, magnetism, heat, and light, as of "chemical actions in the more restricted sense of the word."[367] Those "actions" were themselves rarely referred to as "forces."

One of the motifs introduced as early as 1811 and 1822 that received greater attention in Ørsted's later writings was the identification of that which is unchangeable, indestructible, or imperishable in nature. To the laws and fundamental forces of nature he added the unchangeable rational will of God that is the source of those laws and fundamental forces. The central question of a late dialogue on "The spiritual in the corporeal" was what constitutes the perishable and the imperishable (*det Forgjængelige* and *det Uforgjængelige*) in nature.[368] All individual plants and animals eventually perish, the earth itself is subject to perpetual change, and even objects that appear to have remained unchanged over many centuries have not been wholly inactive, their apparent rest being "nothing but a hovering between equal opposing forces."[369] The answer given by one of the interlocutors is that, "besides nature's fundamental forces, the creative forces, there is nothing else constant in things than the laws of nature by which everything in it takes place," wherefore "these laws of nature could rightly be called nature's thoughts [*Naturtanker*]."[370] The essence of a thing is given by the totality of the laws (i.e., thoughts) of nature that produce and sustain it, a totality that represents its essence as an idea (*Idee*).

In this work Ørsted expounded an explicit idealism (though without using the term) according to which material objects are the physical manifestation of a fundamental abstract idea. In his last work, an essay entitled "The way from nature to God," he asked: "[I]s there anything constant in the world other than the laws of nature and the reason from which they have their origin?"[371] The answer was that there is undeniably something imperishably active (*noget uforgængeligt Virksomt*) in things: the mutual attraction between bodies

367. Ørsted 1846(1847)b, 119 = 1920, 2, 547.
368. Ørsted ca. 1846/50(1850), 10 ~ 1852, 6.
369. Ørsted ca. 1846/50(1850), 12 ~ 1852, 8.
370. Ørsted ca. 1846/50(1850), 32 ~ 1852, 23.
371. Ørsted 1851b, 13. He later spoke of the imperishability of the world of reason (*Fornuftverden*) and identified the rational will (*Fornuftvillie*) that one encounters in the universe as that which is imperishable in it (46, 47).

presupposes an activity that drives them together; the resistance that bodies exhibit to compression presupposes something active that does the resisting; and the actions of heat likewise presuppose something active that expands bodies, melts them, and transforms them into vapor. "In a certain sense one can say that we encounter manifold activities in nature; but the deeper our investigations go, the more it appears that the differences depend upon the laws by which the active [agency] is distributed in time and space, so that we are led to the thought that all actions derive from one fundamental activity."[372] Noting that existence presents itself to us "as the constant work of an all-pervading force and reason, reason and force," Ørsted concluded that "*that unity of reason and force is God,*" that "insofar as God's will manifests itself in space, it shows itself to us as a force of nature," and that God's will and reason "form an inseparable essence, one creative reason."[373]

While Ørsted's various formulations cannot all be reduced to a unified expression, a roughly consistent general picture emerges from his musings. The source of *activity* in nature is the divine *will*, an infinite creative force that manifests itself in the world as the indestructible fundamental forces of nature whose opposition produces the various actions that are the object of study of experimental natural science, in particular electricity, magnetism, heat, light, and chemical activity. The source of *order* in nature is divine *reason*, which manifests itself in the world as the unchangeable laws of nature that govern all change and define the essence of things. Although Ørsted did not use the term in these contexts, it is clear that the original creative force of God corresponds to what he elsewhere termed the primordial force, the *Urkraft*, the singular active source of nature's manifold activities. It is clear, too, how the double meaning of *Yttringer* and *Aeußerungen*—as both "expressions" and "manifestations"—appropriately captures the sense in which the phenomena *are* expressions of God's rational will. All activity in nature has, ultimately, a common conscious source. Although both the laws and the fundamental forces of nature are in a sense constant, there is an important difference: the laws are rigorously fixed and unchangeable, whereas the forces, though imperishable, are themselves in a state of constant change, and their potentially infinite creatability is guaranteed not only by their origin in the infinite creative force of God, but also by their origin via the pairwise separation of mutually canceling opposing forces (or motions) out of an indifferent state of only apparent rest. Colding's imperishable forces of nature had no ready place within the conceptual apparatus of Ørsted's natural philosophy, especially when we recall that Ørsted did not consider electricity, magnetism, heat, light, chemical activity, *and motion* themselves to be *the forces* of

372. Ørsted 1851b, 13–14.
373. Ørsted 1851b, 14–15.

nature. The first five represented rather the different manifestations *of* the underlying fundamental forces.

Ørsted's conception of the unity of nature had yet another long-term manifestation in his writings, involving what Wilson Scott termed "Oersted's law of oscillation" after a section in the English translation of Ørsted's "Reflections on the history of chemistry" (1807) entitled "A closer view of the Law of Oscillation in the development of Science, and its beneficial influence."[374] According to the broadest application of this "law," all development in nature, whether in the corporeal or spiritual realm, proceeds via the interplay of alternately predominating opposing forces. As Ørsted put it, after noting that the history of chemistry displays an alternation between creative periods of discovery and succeeding periods in which the new ideas are clarified and ordered,[375]

> Throughout all history there thus go a creating and an ordering (or an expanding and a restricting) force, whose law it doubtless is that the one must diminish as the other increases. They thus cannot not help but be in constant conflict, and in their most powerful collisions even break out into war. At first glance this might well appear to be hazardous to the progress of our spirit; but does not our own corporeal life subsist through a conflict between opposing forces? Can the spiritual life, in its finite form, manifest itself otherwise? It is a law for the material realm [*for den materielle Natur*] that one of the opposing forces always arouses the other; it is that no less in the spiritual realm [*i den aandelige*].

This correspondence between nature and spirit is not coincidental, but indicates that both are shoots from a common root, that both obey the same laws, and that everything in nature develops toward a common life—and where development is possible only when the opposing forces have gone from equilibrium to conflict.[376] The qualification in the quoted passage ("the spiritual

374. Scott 1975, 254; Ørsted 1852, 320; cf. Hauch 1852, 155–161 and Wilson 1998, xlv–xlvi. Ørsted added the heading "Nähere Betrachtung des Oscillationsgesetzes in der Entwickelung der Wissenschaft, und Wohlthätigkeit desselben," in Ørsted 1850–51a, *2*, 420; it does not appear in Ørsted 1850–51b, *3*, 169. He similarly added the heading, "Nærmere Betragtning af Svingningsloven for Videnskabens Udvikling og sammes velgjørende Indflydelse," in Ørsted 1851–52, *5*, 28.

375. Ørsted 1807a, 49–50 (= 1851–52, *5*, 29–30) ~ 1807b, 228 (= 1920, *1*, 341) ~ 1852, 321–322. The German has "dem Fortgange des menschlichen Geistes" instead of the Danish version's "vor Aands Fremgang" and "Kampf zweier entgegengesetzten Kräfte" instead of "Kamp mellem modsatte Kræfter" in the third sentence. Cf. 51 (= 30–31); 229 (= 342). He expressed essentially the same sentiment in his last essay, "The way from nature to God:" "Human beings' development occurred through a series of uniting and separating activities, of which now one, now the other, at different times and places, became predominant. We will gradually get to see that it is one of the laws of all finite existence that the activities alternate in such fashion and, with this ceaseless conflict, produce and order the objects [of the world]" (1851b, 24).

376. Ørsted 1807a, 52–53 (= 1851–52, *5*, 31–32) ~ 1807b, 230 (= 1920, *1*, 343) ~ 1852, 323.

life, in its finite form") would seem to imply that the spiritual life also has an infinite form, one in which it does *not* manifest itself through the conflict of opposing forces, one like Ørsted's God-like singular *Urkraft*.

Years later, in sketching views that had prevailed before 1820 about the relationship between electricity and magnetism, Ørsted reintroduced this basic conception in somewhat new dress:[377]

> One class of natural philosophers have always a tendency to combine the phenomena and to discover their analogies, another class, on the contrary, employ all their efforts in showing the disparities of things. Both tendencies are necessary for the perfection of science, the one for its progress, the other for its correctness. The philosophers of the first of these classes are guided by the sense of unity throughout nature; the philosophers of the second have their minds more directed towards the certainty of our knowledge....This conflict of opinions keeps science alive, and promotes it by an oscillatory progress, though it seems to the common eye a mere fluctuation, without any definite purpose.

In a late work, Ørsted argued that human beings alternate between superstition and unbelief, between too-ready acceptance and too-ready rejection of religious claims. Here, too, opposites (or antitheses, *Modsætninger*) call each other forth without either being able to achieve lasting predominance.[378] He appealed for a just estimation of the positive and negative aspects of these opposing tendencies:[379]

> We have seen that unbelief consists in a tendency to reject what human beings are accustomed to accept concerning spiritual things insofar as it is only acquired with an immediate internal sense and is not proven with thought; it arises on account of the numerous instances where the discoveries of science refute the opinions one had accepted without investigation....It is natural that this engenders doubt toward the whole kind of knowledge that is so often found in error; doubt goes over easily into mistrust, mistrust with many into an excessive tendency to reject; to this there is added an elevated feeling of the power of thought, which in itself is such a glorious feeling, but which with many degenerates into arrogance.

Thus from the opposition of the two fundamental forces of nature to historical patterns of change with regard to both science and religious belief—running the gamut defined by the extremes of the worlds of nature and spirit—Ørsted's universe played itself out in terms of a ceaseless conflict between opposing forces and tendencies. The "common root" from which these patterns derive is evidently the Author of the world, its supreme lawgiver.[380]

377. Ørsted 1827(1830), 573–574 = 1920, *2*, 352; mostly quoted in Williams 1965, 137. The implied complementarity between the demands of an expansive creativity and a contractive desire for certainty curiously prefigures Bohr's philosophy of nature.

378. Ørsted ca. late 1840s(1850), 85, 106, 118 ~ 1852, 60–61, 77, 87.

379. Ørsted ca. late 1840s(1850), 105 ~ 1852, 76–77.

380. *Fælles Rod* bzw. *gemeinschaftliche Wurzel* in Ørsted 1807a, 53 (= 1851–52, *5*, 31) ~ 1807b, 230 (= 1920, *1*, 343) ~ 1852, 323.

6. ASSESSMENT AND CONCLUSIONS

Colding, Ørsted, and force

The foregoing presentation has made implicitly clear the many ways in which Colding's and Ørsted's work both shared important commonalities and displayed important differences. Both of those features pertain in particular to the central concept of force. Yet given its centrality for both men, its lack of precise and explicit specification is striking. For Ørsted, force—usually conceived pairwise as opposing forces—remained attached to its roots in Kant and Schelling as that which constitutes matter and is the source of all activity in the world. At one side of its conceptual field, it was identified that which determines the properties of things. Elsewhere, and more regularly, forces were identified as that which is active in producing the phenomena of electricity, magnetism, electromagnetism, chemical activity, heat, and light. Those activities—of which Ørsted never provided an explicit and complete enumeration and to which he never assigned a specific generic designation—were regarded as the manifestations (or expressions) of the underlying fundamental forces, whose different forms of action it is the business of a philosophically guided experimental science to determine. Thus aside from the occasional odd usage, Ørsted never referred to electricity and the rest as themselves forces, and the unity of forces that some commentators have spoken of as characteristic of his conception of nature had a profoundly different meaning for him than it has for those for whom electricity and the rest are the forces of nature. For Ørsted pairs of opposing forces arise by way of a process of differentiation of an undifferentiated ground state of a primordial force roughly corresponding to the state of indifference described in Schelling's *Naturphilosophie*.

The analogy invoked the decomposition of forces and motions in mechanics—where any given force or motion, even one of zero magnitude, can give rise to equal and opposite forces or motions of arbitrary magnitude—entailed the possibility that, under proper circumstances, essentially indefinite quantities of forces can be generated from nothing, just as the corresponding composition of forces and motions, combined with the postulated equality of the fundamental forces' opposing actions, entailed the possibility of their mutual neutralization or self-cancellation. In Ørsted's telling

image, the fundamental forces that lie dormant in all things are aroused into action by an external cause, the specific form of that action determining whether those forces manifest themselves as heat, light, electricity, magnetism, electromagnetism, or chemical activity. Ørsted's several attempts at specifying how these forms of action differ—in terms now of the dimensionality of space (as with electricity, magnetism, and chemical action), now of speed or rapidity (as with heat and light), now of the geometrical shape of the action (as with the spiraling action of electromagnetism)—never achieved general and consistent application to all forms of action of the fundamental forces.

Working against the precise circumscription of force as an entity or substance *sui generis* was the very construction of matter out of opposing forces, which blurred any ontological distinction between matter and force. Nor was this situation changed when, in later years, Ørsted adopted an explicitly aetherial interpretation of light, heat, and the rest. If, to be sure, Ørsted regarded forces as active causes and the activity of electricity and the rest as the manifestation of the action of the fundamental forces in one of their distinctive forms, he never pressed a causal characterization of force to its logical conclusion as a generic definition. Here, too, his habit of assigning motion and "chemical" activities to distinct sciences must have worked against the transference to the latter of qualities and quantities more commonly associated with the former. Nor did his ultimate tracing back of forces to the will of God contribute to the circumscription of their meaning in physics.[381] As was also true with Colding, the desire to expand the scope of his natural philosophy worked against the delimitation of its central concepts. It is important to note that these deficiencies in Ørsted's physics pertain to its own concepts and sphere of application, and are not simply the product of a retrospectively identified failure to anticipate the conservation of energy.

Like Ørsted, Colding expounded no consistent or explicit ontology of force, though he did occasionally speak of forces as "actually existing entities," which lent them a vague autonomy from matter.[382] It is impossible to make out from Colding's writings just what he conceived light, radiant heat, electricity, and magnetism to consist in. In an atypical passage from a late work Colding echoed an Ørsted-like belief in "a single fundamental force that can assume all the different forms in which we recognize the forces of nature," but he did not develop this idea.[383] Nor, like Ørsted, did he ever seek to characterize in a generic fashion what he understood to be the forces of

381. The connection between force and will seems to have been especially characteristic of British natural philosophers; cf. Caneva 1993, 221 and 369, n. 13.

382. See the passages quoted at notes 146 and 148.

383. See the passage quoted at note 85. Given the context of the passage, it seems likely that he was intentionally invoking Ørsted's language.

nature, typically contenting himself with the truncated enumeration of "electricity, heat, etc." and the like. With that, however, he was clear that electricity, magnetism, heat, light, and chemical activity *are* the forces of nature, even as he neglected to provide a conceptual characterization of force in general. Like Ørsted, he sometimes spoke of forces as that which gives bodies their properties, although he did not explicitly invoke the construction of matter out of attractive and repulsive fundamental forces. For both men the development of nature is governed by the action of its forces. But unlike Ørsted, Colding more characteristically and explicitly regarded forces as causes of change—especially as causes of change in motion, as producers of motion—known in terms of their effects, and in his later writings he implicitly recognized the doing of work as the cardinal defining feature of forces. Yet even at that he appears not to have appreciated, as Mayer did, that the spatial separation of masses subject to gravitational attraction is itself a cause capable of producing motion and hence must somehow be assimilated into a universal principle governing the action of forces. (Causal considerations played an important role in Mayer's, Helmholtz', and Carl Friedrich Mohr's energy-like conceptualizations of force.) Neither Colding nor Ørsted glimpsed anything like the concept of potential energy. Although Colding extended his principle of the imperishability of the forces of nature to electricity, magnetism, chemical activity, and light, in fact he devoted most of his attention to motion and heat. His attachment to the explanation of heat in terms of the motion of the smallest particles of bodies played a pivotal role in his theoretical reflections: that was the bridge that enabled him to see motion and heat as the same kind of thing, the kind of thing that can itself be the cause of further motions. For Colding there was thus a real transformation of motion into heat, whereas for Ørsted the process was an example of the stimulated calling forth of the activity of opposing forces that had lain dormant in the body all along.

We can now appreciate the character of Ørsted's unappreciative response to Colding's assertion of the imperishability of the forces of nature. Part of the context was shaped by Ørsted's attachment to a conception of forces and motions, whether mechanical or "chemical," as always existing in equal and opposing magnitudes the sum of which must always be zero. This conception entailed not only the possibility of the generation of indefinitely large amounts of force, but also guaranteed that opposing forces and motions must be able to neutralize each other, that is, to perish. If, in 1799, Ørsted entertained the Kantian notion that substance can be neither increased nor diminished in quantity, his subsequent understanding of forces as properties of bodies having no independent ontological existence effectively removed them from the reach of such considerations. I thus concur in Gower's conclusion that "his dynamical theories of physical action, with their emphasis upon the interaction of polar forces, contributed little to the creation of a conceptual framework

within which the energy conservation principle could emerge and be understood....For this principle involved the idea that some physical *quantity* is conserved under transformation."[384] Ørsted's conception of the relationship among the various forces of nature did not prompt him to think in terms of transformation, let alone quantitative constancy.

Naturphilosophie and the conservation of energy

Gower qualified in one important regard the negative conclusion to which he had arrived on the basis of his examination not only of Ørsted's scientific work but also of Schelling's *Naturphilosophie*: "*Naturphilosophie* might be said to have provided a possible philosophical context for the metaphysical, qualitative, superstructure of the energy conservation principle, but the efforts of scientists like Ritter and Oersted who were prepared to accept this context could have been to no avail if scientists like Faraday, Joule, Mayer and Helmholtz had not successfully striven to provide the detailed experimental substructure."[385] Other students of Ørsted's work have been less qualified in their assessment of the importance of *Naturphilosophie* to the formulation of the principle of the conservation of energy. For Ole Knudsen, the idea of the unity among the forces and phenomena of nature, as of that between nature and the human spirit—an idea he traced to Schelling's romantic natural philosophy—"was doubtLess an important precondition for the formulation of the principle of the conservation of energy in the 1840s."[386] In the estimation of Andrew Wilson, "[f]or at least a handful of physicists, this [i.e., Ørsted's] view of a force-filled universe provided the key for the further understanding of the unity of physical forces. It also provided the starting point for the development of the concept of physical lines of force and for the development of classical field theory, and prepared the way for the discovery of the conservation of energy."[387] Although one can imaginatively construct possible routes from the conceptual world of *Naturphilosophie* to one conducive to conservation-like reflections, no one actually went that route.[388] Indeed, Ørsted provides a vivid example of just why such a passage was extremely unlikely.

Kuhn's influential study of 1959 suggested that "*Naturphilosophie* could...have provided an appropriate philosophical background for the discovery of energy conservation" as it identified, probably for the first time, Ørsted's protégé Colding as someone familiar with its teachings.[389] With time

384. Gower 1973, 349.
385. Gower 1973, 349.
386. Knudsen 1987, 58.
387. Wilson 1993, 603.
388. I have dealt extensively with this topic in Caneva 1993, xxii, 275–319; 1997, 67–71.
389. Kuhn 1959, 338–339, on 338.

and without dissenting voices this suggestion has hardened into historical fact, so that the otherwise careful and insightful Fabio Sebastiani could identify Colding as a "student of H.C. Oersted and hence strongly influenced by *Naturphilosophie*.[390] Even Per Dahl, who otherwise expressed appreciable diffidence with regard to the metaphysical aspects of Colding's work, followed Kuhn in accepting that *Naturphilosophie* was an important part of the intellectual environment out of which the principle of the conservation of energy emerged.[391] In his review of Dahl's book, Henry Steffens went even further:[392]

> Colding's work, as well as that of Joule and Mayer, can be meaningfully linked to German philosophy. Recent work on *Naturphilosophie* is of special importance to an understanding of the formulation of the conservation of energy principle. What is now needed are detailed studies of the individuals espousing the conservation principle in terms of their discernible philosophical and religious preconceptions...
>
> Dahl's work on Ludvig Colding provides the opportunity to study the specific importance of *Naturphilosophie* to the espousal of the energy principle.

Alas for such claims, detailed study of Mayer and Colding—not to mention Helmholtz, another of Kuhn's candidates—has failed to sustain the widely alleged importance of *Naturphilosophie* to the emergence of the principle of the conservation of energy. For Mayer, religious and philosophical considerations indeed played a crucial role, but they are not usefully or accurately characterized as *naturphilosophisch*. With Colding the situation is more complicated. He was, to be sure, strongly influenced by Ørsted's belief in the correspondence between our rationality, God's rational will, and the unchanging rational character of the laws and forces of nature—beliefs that owed much, in a general way, to Schelling's philosophy of nature. As Colding wrote, echoing Ørsted, "nature's forces are an expression of the spirit that pervades nature."[393] They represent the most exalted and sublime aspect of nature. Moreover Ørsted clearly raised the issue of what constitutes the unchangeable or imperishable part of nature, even as, for him, the answer seemed to be in terms of nature's invariable *laws*.

Yet important as they were, such notions by themselves did not prompt the likes of Schelling and Ørsted to formulate a conception of force that was amenable to conservation-like considerations. On the contrary, it was precisely the closeness of Ørsted's conception of force to its origins in Kant's and Schelling's natural philosophies that made it difficult for him even to

390. Sebastiani 1987, 154.
391. Dahl 1972, xxiii; cf. xxxiii.
392. Steffens 1974, 122.
393. See the passage quoted at note 145.

appreciate the radically different conception of force that underlay Colding's reflections. By itself, belief in the unity of nature is too vague a notion to have encouraged the clarification of a concept of force amenable to conservation-like considerations. Nor did Ørsted's belief in the unity of forces afford an effective guide, especially since that unity and those forces were conceived in a fashion quite unlike the meaning that came to be associated with 'the unity of force' only *after* the general clarification of something like the modern conceptions of energy and its conservation. Attention to the question of the *conservation* of energy has, I believe, obscured the difficulty of formulating a concept of *energy*, under whatever name, about which it is meaningful to ask conservation-like questions. Ørsted's forces did not belong to that class. Nor are alleged examples of 'transformation' always what they have appeared to some commentators.

Colding and the imperishability of the forces of nature

Colding's route to belief in the imperishability of the forces of nature resulted from the interaction of a number of identifiably distinct moments. As he repeatedly reported, his starting point was an unshakable conviction in the close relationship between the forces of nature and its spiritual aspect, including the human spirit: if our spirit is imperishable, then so, too, must be nature's forces. Here Ørsted's belief in the rational unity of nature and the indestructibility of the fundamental forces of nature played a central role, though the passage of this conviction from Ørsted to Colding was accompanied by an important shift in the meaning of the concept of force: from opposing and self-neutralizing pairs of forces after the model of the fundamental forces constitutive of matter, to forces regarded as activities, as causes of motion in the physical world. The idea that an activity might be able to disappear without a trace, without reappearing as an active cause under some other form, thus struck Colding as against reason. In particular, cases where mechanical living force (*vis viva*) appears to be lost while accompanied by the appearance of heat implied to him that that lost living force must be *transformed* into heat, which he interpreted as the motion of the smallest particles of bodies. Crucial here was Colding's attachment to the atomic theory of matter; his close early collaboration with Ørsted on the experimental investigation of the heat produced by the compression of water may also have contributed to his developing views. Colding's choice to investigate the relationship between motion and heat in terms of the frictional heat generated by an applied force working against resistance to motion was thus closely connected to his theoretical reflections. The phenomenon itself, of course, had long been of particular interest to both experimentalists and theorists of heat.

The several places where Colding explicitly addressed and rejected the possibility that one force might merely call forth the action of another, without involving any kind of transformation, would appear to have been tacitly addressed to Ørsted's habitual way of regarding the phenomena. Ørsted and Colding both spoke of the different forms that the different forces of nature can assume, but they attached very different meanings to those same words. Somewhere in the extended process by which he clarified his ideas, Colding recalled what he termed d'Alembert's principle of lost forces, and had to address what appeared to be a challenge to his initial but nevertheless strong belief in the imperishability of the forces and activities of nature. (Note that Colding never spoke of the imperishability of force, in the singular.) He resolved this temporarily disconcerting anomaly by distinguishing, in his own rough fashion, between forces in equilibrium that do no work and those that contribute to the creation or destruction of motion—a crucial step toward the clarification of an energy-like conception of force. He gradually made clearer and more explicit the centrality of the performance of work as both the fundamental characteristic and the *measure* of the activity of a force, a clarification doubtless much facilitated by his familiarity with both the theory and practice of machines. Colding's professional education as an engineer made accessible to him the technical literature, from Clapeyron on, that assimilated the treatment of heat to the conceptual and symbolic apparatus of analytical mechanics. Though his achievements in this regard were even less known than his experimental and conceptual work, they exhibited the sureness of his grasp and the cogency of that assimilation.

Although he never formalized his terminology—and despite the fact that he kept the language of "the imperishability of the forces of nature"—Colding came in practice to use the word activity in ways very close to the denotation of the then-developing concept of energy. Ironically, given the origination of his reflections on the imperishability of forces in his belief in the correspondence between the human spirit and the forces of nature, in 1856 he expressed the idea that the progressive development of the forces of nature is accompanied by their eventual transformation into "the spiritual life," into the spiritual activity of thought, implying that the total quantity of activity in the physical world must be continually decreasing. Thus, as we have seen before, the desire to extend the scope of a concept can work against its precise circumscription, nicely exhibiting Ørsted's image of the complementarity between an expansive creativity on the one hand and, on the other, the desire for clarity and certainty that works toward the protective contraction of one's claims.

Colding and Mayer

Part of the initial motivation behind this study was an interest in investigating what appeared to be intriguing similarities between Colding's and Mayer's routes to their respective conservation principles. Both received a solid professional education, Mayer in medicine and physiology, with a little chemistry and physics, Colding in engineering and mathematics. Neither held an academic position in science, nor did either succeed in attracting meaningful attention from the larger scientific community early in his career, when it might have mattered either to him personally or to science. Each was drawn to a certain notion of the indestructibility of force by considerations of a fundamentally metaphysical or theological nature, each focused in the first instance on the relationship between motion and heat, and each sought experimental corroboration for the theoretically necessary quantitative equivalence between work and heat. That the technically much more competent Colding apparently did not see how to exploit existing data on the compression and thermal expansion of gases as did Mayer underscores both the brilliance and the nonobvious character of Mayer's achievement. Crucial in each case were certain insights derived from mechanics, in Mayer's case most importantly the use of the distance through which a body falls as a measure of its quantity of motion (the latter thus clearly $\frac{1}{2}mv^2$ and not mv), for Colding the clarification of the concept of work as the measure of the action of a force. Curiously, considering both their concerns and the wholly independent example of Helmholtz, neither man seems to have drawn any inspiration from the well known principle of the conservation of *vis viva*. Again despite Colding's incomparably greater technical competence, only Mayer, in his conception of fallforce, had a clear sense of the importance of what we term potential energy. Indeed, Colding explicitly rejected that aspect of Mayer's work.

In each man's work one can distinguish between an overarching theory of the interconnectedness and quantitative constancy of the forces of nature and a narrower assertion of the mechanical equivalence of heat and the calculation of its numerical value. Each perceived the latter to be the scientifically more readily acceptable aspect of his work, even as he regarded the larger philosophical context as of intrinsically greater significance. Extending the field of meaning of the central concept of force beyond its applications in mechanics and physics, each saw his conception of force as a refutation of ontological materialism. Colding's enthusiasm for Eschricht's defense of a vital spirit reveals the depth of his commitment to an ontology richer than just matter in motion, although there is no evidence that he was particularly stimulated by issues raised in the physiological literature concerning the creation and destruction of the vital force at the birth and death of the individual.[394] Colding

394. On this and other aspects of the physiological context to Mayer's work, see Caneva 1993, 79–142, 150–152.

did not, like Mayer, address the issue of the substantiality of force, nor did he pay significant attention to the issue of its creatability. In clarifying for themselves the meaning of force, both Colding and Mayer pondered the significance of cause-and-effect relationships and found it necessary to argue for the distinction between the material effects of a cause (the wood sawn by a water mill or the metal filings produced by mechanical action) and its more properly 'dynamical' effects (the new manifestation of the forces that effected the given changes). In Mayer's case, at least, that clarification lifted an earlier confusion; Colding may merely have been addressing what he anticipated might be others' confusion.

There was, finally, appreciable difference in the precision with which each man circumscribed the concept of force. Colding's conception of force was still occasionally attached to the understanding of forces as properties of things, and his willingness to entertain the possibility of the transformation of physical force into spiritual activity meant that the forces of physical nature are not in principle sharply delimitable. Mayer's exploitation of an *analogy* between force and spirit avoided the problem attendant upon Colding's assertion of an ontological *identity*. Although neither theorist introduced a distinctive term for his reconceptualization of force, the lack was more serious for Colding because he also lacked a precise *concept* of force as energy. Unlike Mayer, who from an early stage wrestled with the problem of how to define forces vis-à-vis causes, material substances, and the imponderables, Colding never provided a *general* characterization of the meaning of the term, but rather contented himself typically with a truncated enumeration of "the forces of nature." Although Colding's presentation of his theory, in its impressive mathematical dress, was incomparably more sophisticated than anything Mayer could even have understood, it was Mayer who saw more clearly the need for conceptual precision and who addressed such problems with greater consequentiality. It was thus Mayer who more successfully marked out the empty conceptual space around force, just as, by abolishing the traditional notion of imponderables, he secured enough empty conceptual space around matter to warrant making *its* conservation a matter of principle.[395]

Historiographical implications

Beyond its attention to particular aspects of Colding's and Ørsted's work, this study has sought to illustrate the process of concept formation in science:

395. Caneva 1993, 205 and 376, n. 212; cf. Caneva 1994, 29. Recall in this regard the lack of separation between Ørsted's conceptions of matter and force, and cf. the passage quoted in note 349.

where general notions come from; how analogies and ontological commitments affect the range of possibilities considered; how fields of meaning are surveyed and staked out and thus how language crystallizes into meaningful patterns; how observation and experiment both affect and are affected by the scientist's theoretical concerns; and how that process is guided by insights derived from the technical-mathematical language of science. A nice example of what one might term progressive terminological hardening is afforded by the progression from d'Alembert's talk about "the forces lost" in certain interactions to Poisson's conceptualization of "lost forces" to Ramus' statement of "d'Alembert's principle for the equilibrium of the lost forces" to Colding's invocation of "d'Alembert's principle of lost forces."

Methodologically speaking, if this study has illustrated anything in general it is the importance of paying attention to the nuances of meaning in the language of the scientists being studied. Failure to do so has been the principal obstacle to an accurate understanding of Ørsted's concept of force, of the relationship of the conservation of energy to *Naturphilosophie*, and of Colding's intellectual antecedents. A more than merely useful exercise is to force oneself not to use language foreign to one's subjects in restating what it was they said and did. It is then obvious that electricity, magnetism, heat, light, and chemical activity were not, for Ørsted, themselves the forces of nature, that Schelling did not formulate a principle of the unity of force, and that Colding propounded neither a well-defined concept of force nor a principle of the imperishability of force. With both Ørsted and Colding the difference between talking about *force* and talking about *forces* is of great significance: a general concept is not the same thing as an enumerable set of particulars. If the example of Ørsted demonstrates how the absence of a particular term betokens the likely absence of a unifying concept, then the example of Colding illustrates how the existence of a term may nevertheless obscure the user's lack of conceptual clarity.

Although it would be rash to generalize broadly on the basis of this study, nevertheless its findings, together with those of my study of Mayer, strongly suggest the extent to which, during periods of conceptual change in particular, an individual scientist's meanings cannot be inferred from a supposed consensus of the ostensible scientific community, however much those meanings draw from that community, but instead must be derived from broad and careful reading of the person's own works.[396] However much Ørsted and Colding, like Mayer, were creatures of their contexts—and each fits quite comfortably

396. I thus agree with Steffens that "[a] detailed assessment of the ways in which each of the 'simultaneous discoverers,' working with different information and in different cultural milieus, came to their understanding of the concept of the imperishability of forces, offers the possibility of a deeper understanding of the nature of scientific creativity" (1974, 122).

into his time and place—those contexts were *necessarily* defined uniquely for each individual. How consensus was reached during the second half of the nineteenth century about the scope and meaning of the concept of energy as well as about the different associations of a broadly conceived principle of the conservation of energy and of the more restricted mechanical equivalence of heat—indeed *whether* any such consensus was reached—must remain the subject of a future study.

Timeline

1777 August 14: birth of Hans Christian Ørsted in Rudkøbing, Langeland, Denmark

1798: publication of Schelling's *On the world soul*

1800: publication of Winterl's *Introduction to the chemistry of the nineteenth century*

1803: publication of second edition of Schelling's *Ideas for a philosophy of nature*

1808 November 15: Ørsted elected member of the Academy of Sciences

1815 January 20: Ørsted elected secretary of the Academy of Sciences

1815 July 13: birth of Ludvig August Colding near Holbæk, Sjælland, Denmark, as the youngest of two sons

1836: Colding became journeyman cabinet-maker (*Snedkersvend*)

1837: Colding took both the general preparatory examination and the entrance examination to the Polytechnic School in Copenhagen; entered the school as an *Examinand*

1839: Colding began to ponder the imperishability of the forces of nature

1839 February 15: Ørsted applied to the Academy of Sciences for funds to continue his experiments on the compressibility of water; Colding assisted him and performed the calculations

1840 July 3-9: first meeting of Scandinavian scientists in Copenhagen, at which Colding considered presenting his ideas

1841 January 14: Colding became engaged to his cousin, Henriette Louise Lange (1816–1873)

1841 April 5: Colding took examination in mechanics; graduated as *polytechnisk Candidat i Mechanik*

1843 November 1: Colding presented first paper, "Some propositions concerning forces" (1843[1856]), to the Academy of Sciences; concluded "that the quantities of heat produced are in all cases proportional to the lost moving forces"

1843 December 10: Ørsted's report (1843[1920]) on Colding 1843(1856)

1843 December 15: Ramus' report (1843[1920]) on Colding 1843(1856)

1844 January 4: report of Ørsted, Ramus, and Hoffmann (1844[1845]) on Colding 1843(1856), delivered at meeting of January 5; the first published account of Colding's work

1845 July 28: Colding appointed Inspector of Roads and Bridges in Copenhagen (a position he held until 1886)

1845 October: date of Colding's unpublished paper, "On the loss of forces" (1845[MS])

1845 November 14: Colding's marriage

1847 July 12: Colding presented paper, "On the universal forces of nature and their mutual dependence" (1847[1849]), at the fifth meeting of Scandinavian scientists in Copenhagen; announced result that "1 lb. of water heated 1 degree celsius = 1185 ft.-lbs"; Colding's first published paper

1848 Mar 3: Colding presented paper, "Investigation concerning the universal forces of nature and their mutual dependence and especially concerning the heat developed by the friction of certain solid bodies" (1848[1850]=1848[1851]), to the Academy of Sciences

1848 December 13: Ørsted's report (1848) on Colding 1848(1850); first publication of Colding's finding that "1 pound of water heated 1 degree celsius can be expressed by 1185 pounds raised 1 foot"

1849 November 16: Colding presented paper, "On the universal forces of nature and their mutual dependence" (1849[1850]=1849[1851]), to the Academy of Sciences

1850: publication of Mynster 1850, which prompted Ørsted to publish the second volume of *The spirit in nature*

1851 March 9: Ørsted's death

1851 May 4: Colding presented paper, "Investigation concerning steam and its motive force in steam engines" (1851[1852]=1851[1853]), to the Academy of Sciences

1852 January 15: Ramus' report (1852a) on Colding 1851(1852)

1856 February 22: Colding presented paper, "Scientific reflections on the relationship between the spiritual life's activity and the universal forces of nature" (1856), to the Academy of Sciences; defended principle of "the imperishability of forces"

1856 April 11: Colding elected to membership in the Academy of Sciences

1863 November: date of Colding's essay, "On the history of the principle of the conservation of energy" (1863[1864]), published in *Philosophical magazine*

1864 June: Colding completed essay for the Paris Academy's Prix Bordin bearing the motto, "What nature is, it owes to the forces of nature" (1864a[MS]); defended the "law of nature" that "the forces of nature are in essence imperishable"

1888 March 21: Colding's death in Copenhagen

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Note: Primary-source papers (though not books) are dated in the first instance according to their year of composition. If a paper was published in a different year, that year appears afterwards in parentheses. If a work is quoted here from manuscript, the letters "MS" appear in parentheses after the year of composition. A date such as "1834–41" indicates that a (typically multipart) work appeared over the indicated span of years. A date such as "1845/46" indicates uncertainty as to the exact dating of the work in question. The dating "1843;1845," a form uniquely applied to a work of Ørsted's, indicates a work printed in 1843 but not published until 1845. Pagination of books is given when deemed useful here. Volume numbers are italicized; the number of the issue, number, *Stück, cahier*, etc. appears in parentheses after the volume number or journal title, somtimes also followed by the month. The following abbreviations are used for journals cited more than once:

ACP = Annales de chimie et de physique;

AP = Annals of Philosophy;

APC = Annalen der Physik und Chemie; the last-given and highest volume number in parentheses is that of the entire series ("der ganzen Folge"), i.e., including the earlier *Annalen der Physik*;

BPMO = Bibliothek for Physik, Medicin og Oekonomie;

DVSA = Det Kongelige danske Videnskabernes Selskabs philosophiske og historiske Afhandlinger;

DVSO fra xx til yy = Oversigt over det Kongelige Danske Videnskabernes Selskabs Forhandlinger og dets Medlemmers Arbeider fra xx til yy;

DVSO i Aaret xx = Oversigt over det Kgl. [bzw. *Kongelige] danske Videnskabernes Selskabs Forhandlinger og dets Medlemmers Arbeider i Aaret xx*;

DVSS = Det Kongelige Danske Videnskabernes Selskabs Skrifter; all volumes cited are from the "Naturvidenskabelig og mathematisk Afdeling";

JdCP = Jahrbuch der Chemie und Physik;

JfCP = Journal für Chemie und Physik;

KLE for Aar xx = Kjøbenhavnske lærde Efterretninger for Aar xx;

PM = The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science;

SLS = Det skandinaviske Litteraturselskabs Skrifter.

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