6 Darwin's Relevance for Nineteenth-Century Physics and Physicists: A Comparative Study

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Introduction: Darwin in physics?

When the *physicist* Ernst Mach states that Charles Darwin's 'special great discoveries' could 'by no means have been made by a physicist' (Mach 1991, 197), this seems at first glance trivial and tautological: physics traditionally has to do with inorganic nature and its laws, while Darwin's focus was precisely on animate nature, on the origin and explanation of its species.[1] On this basis, Mach's remark appears only too logical. If on the other hand *non-physicists* pronounce Darwin to be 'the Copernicus of the organic world' (Emil Du Bois-Reymond), the new 'Galileo' (Asa Gray) or allude to him as the 'Newton of the grass blade' who – after Kant – should never have been (Ernst Haeckel), they are also stating that Darwin made discoveries of revolutionary significance which changed accepted conceptions of the world – a circumstance that up to that point was only known within the fields of physics[2] and was presumably expected only of that science. This is concisely presented in Du Bois-Reymond's comparison of Darwin with Copernicus. He emphasizes the contribution of both scientists to the overcoming of anthropocentrism: the heliocentric system of Copernicus denied man his cosmological status in the centre of the universe; Darwin's theory of evolution also denied him his exclusive status within the living world of nature as the only animate being superior to any animal.[3]

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1 This chapter is an abridged and slightly revised version of Pulte 1995. I would like to thank Mechthild Droste-Pulte for the initial English translation and for critical remarks.

2 *Physics* is used throughout this paper in a wide sense, including astronomy (explicitly in respect to Copernicus) and mathematical physics. An extensive historical and systematic examination of the influence of the Darwinian revolution on the so-called exact sciences has still to be performed. Such a study would have to analyse physics, but also the development of basic principles of geometry (W. K. Clifford, H. Poincaré and others).

3 Du Bois-Reymond 1912, 244–46. Although Darwin is often compared with Copernicus, the focus of such studies varies (see Freud 1952–68, 12.8,11; 11.294–95).

Darwin – the Copernicus, Galileo or Newton of the century. All these comparisons point, however, to an aspect which has been of little relevance in critical works on the Darwin reception. This aspect is best described with the term *physico-centrism*: physics, with its more and more differentiated experimental methods, as well as its growing mathematization in the nineteenth century, set methodological standards for all sciences and characterized the contemporary theory of science of whatever origin. In 1859, when Darwin's *Origin of Species* was published, its first laws, especially the principles of mechanics, were still considered to be universally valid, certain and unchanging.[4] They were especially regarded as the solid foundation of any future natural history research. At least within physics reductionism (of varying interpretation) was predominant. It taught that all processes of nature should directly be traced back to physical processes or should at least in investigating them proceed according to methodological standards of physics.

Darwin's theory of evolution must have meant a specific challenge to such a *static* physics, because this theory included man and his cognitive abilities from the very beginning (Engels 1989, 66). Physics therefore was confronted with the fact that man – its central apparatus – had become the object of a doctrine of biological development. This *had* to have consequences for physics and physico-centrism.

The relationship between physics and the biological theory of evolution therefore proves to be more complicated than it appears at first. It is the aim of this chapter to expound important aspects of this relationship. Two leading questions are the focus of our attention. In the first place: how was Darwin's theory of evolution received by contemporary physics and which specific discipline-inherent elements and changes intervened?[5] Second: what influence did Darwin's theory exert on the understanding of science within physics itself? Victorian physics, which – like German-speaking physics – dominated the second half of the century, is of primary concern. German physics is mainly represented by two of its most influential scientists, Ernst Mach and Hermann von Helmholtz.

Darwin, Victorian physics and its theory of science

Darwin realized clearly that his doctrine would be judged according to the standards of physics. He himself likewise formulated the aim of revealing general and unchangeable laws for the theory of evolution analogous to Newton's law of gravity for celestial mechanics – the young Darwin intended in fact to become

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4 Mechanics especially followed the axiomatic-deductive ideal of Euclidian geometry but was increasingly criticized from the middle of the nineteenth century to the end (Pulte 2005).

5 As far as the reception in physics is concerned, it has to be assumed that Darwin's theory had a 'catalyst-function' (Bowler 1990, 14, 128), i.e. it promoted non-Darwinian theories of evolution which were characterized by purpose and progress. It is therefore important to draw attention to a Darwinism in a *stricter* sense, that is, different from such theories as it assumes a process that is not directed and based on accidental variation with an open outcome.

the 'Newton of Biology' (Schweber 1979; 1989). At the time when the *Origin of Species* was written the Victorian theory of science was strongly influenced by the *Preliminary Discourse on Natural Philosophy* (1830) of the astronomer John Herschel. For decades the *Discourse* played in Great Britain a similar influential role to that of d'Alembert's *Preliminary Discourse to the Encyclopedia* (1751) in France. Darwin himself intensively studied it and esteemed it highly (Darwin 1858, 67–68). Beside Herschel, one must mention the universal scholar William Whewell, who became famous mainly for his two studies on *The History of the Inductive Sciences* (1837) and *The Philosophy of the Inductive Sciences* (1840).[6]

Both scholars, Herschel and Whewell, can be said to embody the *physico-centrism* in the philosophy of science of their age. Both recognized the highest form and guiding principle of any scientific research in Newton's celestial mechanics. It is useful for the understanding of science in Victorian physics and its reception of Darwin, not to concentrate on their considerable differences but to emphasize some common features in Herschel's and Whewell's theory of science. These are foremost:[7]

(a) the emphasis on *induction* after Bacon and in differentiation from Bacon. For both induction as a (step by step) generalizing, methodologically reflected method is the most important means to gain hypotheses;
(b) the necessity of *deduction* of new empirical statements. Not until predictions of that kind are available can the correctness of inductively gained hypotheses be confirmed;
(c) the possibility of obtaining knowledge about first, general and reliable laws of nature through induction and deduction. These laws are (for Herschel always, for Whewell in advanced sciences) *quantitative* laws;
(d) the sanctioning of the method applied in physics (following Newton) that acknowledged explanations which appear in the most general laws of nature as true causes of a natural process. These laws are expressions of a nature-immanent, genetic causality. The law of gravity in which gravity appears as '*vera causa*' demonstrates this in an exemplary fashion.

All these observations reflect essentially the understanding of science which was held in physics. It can be characterized as *hierarchically-gradualistic* (hypothetical-deductive structure arranged in gradations ordered in hierarchical steps), and it is

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6 The third influential philosopher of science contemporary with Darwin was J. S. Mill. His *System of Logic* (1843), however, had less influence on physics than the works of Herschel and Whewell. He is nevertheless important for the more general reception of Darwin: at the same time as the Mill–Whewell controversy was going on, the intensive discussion of Darwin's *Origin* made a great contribution to a growing sensibility to questions of philosophy of sciences (Ellegård 1958).

7 For the following points see esp. Herschel 1830, (a) 144–48, (b) 164–69, (c) 123–24, 175–76, (d) 144–59 and Whewell 1967, 2: (a) 46–54, 74–75, (b) 62–68, 77–82, (c) 91–93, (d) 96–101, 281–86 (and 1: 700, 164–70). This survey, which is appropriate for physics, is definitely not meant to cover the great differences between the two systems, which in Herschel's case result from an empiricist theory of knowledge whereas Whewell is strongly influenced by Kant. Compare (in respect to Darwin) for instance Hull 1973, 1974 and Ruse 1975, 1979.

committed to *certism* (possibility of recognizing infallible laws), to *prognosticism* (affirmation by prediction) and to *essentialism* (*vera causa*-doctrine).

Darwin himself at first tried to present his theory of evolution in a way that conformed to this concept,[8] and in the first edition of the *Origin* he had also paid tribute to Herschel as well as Whewell.[9] It was surprising, therefore, that both responded to his doctrine in the negative: Herschel and Whewell rejected Darwin's *Origin*, at first even vehemently (Hull 1995). The response of physicists in the stricter sense was no more positive: William Hopkins was one of the earliest and most intense critics of Darwin – just like his pupil William Thomson.[10] Other physicists who were declared opponents of Darwin were Davis Brewster, George Stokes, Peter G. Tait, Belfour Stewart and also the physicist-engineer Fleeming Jenkin.[11] This list could be extended.[12] On the other hand, John Tyndall seems to be the only one of the better known representatives of Victorian physics who supported Darwin's theory of evolution.[13]

This general negative reception needs to be explained. The discussion of objections to Darwin will, however, be limited to typical ones, that is those which are closely related to that concept of science that physics as a discipline held.

Physicists repeatedly brought forward the argument that Darwin's theory did not follow the *inductive method*. On the background of contemporary philosophy of science this criticism was indeed almost devastating, but it was also (and presumably for that reason) a commonplace in the *general* criticism of Darwin (Ellegård 1958, 185ff.). In a more precise sense, however, critics from the physics side meant that Darwin's theory was not preceded by a *good* (i.e. step by step)

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8 'Darwin wanted to make his theory as Newtonian as possible' (Ruse 1979, 16).

9 In his introduction Darwin praises Herschel as 'one of our greatest philosophers' (Darwin 1964, 1; for background, see Schweber 1989, 32); on the front page Darwin honours Whewell with a motto from the *Bridgewater Treatises* – even before Bacon.

10 Compare Hopkins 1973. 'Hopkins' review . . . is thought the best which has appeared against us', Darwin remarks on this review (Darwin 1887, 2: 327).

11 See Jenkin 1973. Darwin regarded this review of the *Origin* as the most useful of all (Darwin, 1887, 2: 107). See furthermore Stokes 1893 (compare also Wilson 1989), Tait 1869, 1876, as well as Stewart and Tait 1875; on the last-mentioned work, Heimann 1972. On the Newton biographer David Brewster's critique of Darwin, see Ellegård 1958, 56, 157.

12 Samuel Haughton (see Haughton 1973), who read geology in Dublin but worked mainly on mathematical physics, can also be counted among the group of vehement physicist critics of Darwin, along with Hopkins, Thomson, Tait and Stokes (Hull 1973, 227); this group was very influential. J. C. Maxwell belonged to a group of more moderate critics of Darwin. He did not intervene in the discussion on the *Origin* but made critical remarks on Darwin's theory of pangenesis (Maxwell 1890, 2: 460–62). Michael Faraday, also one of the great Victorian physicists, seems not to have commented on Darwin's doctrine. As he was very religious (Gooding 1982) it can be assumed that he did not support it.

13 Compare Tyndall 1874, 182–92. Tyndall's role was rather to popularize science than contribute as physicist. Among Victorian physicists he held a special position as he had studied in Germany (Marburg and Berlin). This is interesting with respect to a comparison of the British and German history of reception. Editors' note: on Tyndall, see the essay by Jones in Chapter 3 of this volume.

process of induction. Darwin was accused of arriving at general principles by departing from the solid basis of observation by means of an *inductive jump*. His general principles, variation and natural selection, had therefore to be regarded as 'mere speculations'.[14]

Herschel, as well as Whewell, allows the speculative establishment of hypothesis in principle, but for the rightness of hypothesis they put the whole burden of proof on the second step mentioned earlier on, that is the deduction of new empirical statements.

Darwin's theory of evolution – so critics claimed – cannot, however, provide such confirmations.[15] Darwin himself freely admitted this *prognostic deficiency* – while adding that such deductive confirmations in the case of his theory must be regarded as impossible, if one takes into account the enormous length of time required.[16]

In general, however, he increasingly responded to the physicists' criticism with a claim of *methodological autonomy*: his doctrine was not to be judged according to standards derived from *physics*.[17] Accused of deficient induction and rash speculation, he argues that without a leading (necessarily speculative) theory, induction was not possible at all: 'for without the making of theories I am convinced there would be no observation' (Darwin 1887, 2: 108). That any observation is based on theory serves here especially as an argument against Herschel's inductivism (Charpa 1987, 129ff.), which claims to be in possession of direct empirical access to nature.

Darwin furthermore does not attribute the confirmability and explanatory power of his theory of evolution to a direct deductive proof of new species but to the structuring and grouping of large systems of phenomena. The physicist's hierarchical-gradualist theory concept can be contrasted with Darwin's (to a certain extent) *holistic* concept:

> Some of my critics have said, 'Oh, he is a good observer, but has no power of reasoning.' I do not think that this can be true, for the *Origin of Species* is one long argument from the beginning to the end. (Darwin 1958, 140)[18]

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14 Hopkins (1973, 231) is specific on this point. His criticism follows Whewell's warning about 'insecure' induction (Ellegård 1958, 191). Compare also Whewell's criticism of Darwin (Todhunter 1876 II: 433–34) and Thomson's *Lectures* (Thomson 1891–94, especially 2: 197–99).

15 'The great defect of this theory is the want of all positive proof . . .' (Hopkins 1973, 266). Nearly all 'hard' critics repeated this argument. On the positions of Whewell and Mill, see Hull 1995.

16 See especially Darwin 1876, 278–82 and Darwin 1903 I: 184.

17 Compare Bowler 1990, 163–64 on the controversy on the age of the earth and note 24, below. The general tendency of the biological sciences toward autonomy is shown for example in the plans (developed in 1874 and realized in 1887) to divide the *Philosophical Transactions* into two series: 'A: Mathematical and physical sciences' and 'B: Biological sciences'. See Hall 1984, 116.

18 Compare Darwin 1964, 459. Elsewhere he comments on his doctrine: 'the doctrine must sink or swim according as it groups and explains phenomena. It is really curious how few judge it in this way, which is clearly the right way' (Darwin 1887, 2: 155, 210; 1903, 1: 184).

In this context, Darwin's methodology proves to be more modern (because undogmatic) than that of his physicist critics. His arguments, however, could not find favour with the inductivistic philosophy of science, as the judgement of the physicist Hopkins shows: 'It is impossible [. . .] to admit laxity of reasoning to the naturalist, while we insist on rigorous proof in the physicist. He who appeals to Caesar must be judged by Caesar's law' (Hopkins 1973, 231).

So far, any other theory of evolution could have met the same criticism as has been outlined in the case of Darwin. This reflects the fundamental problem of philosophy of science, still discussed today, in bringing historical theories into a hypothetical- (or even axiomatic-) deductive form, just as it had been in physics.[19]

Objections on the part of physics that affect the *centre* of Darwin's doctrine, i.e. the explanation of the origin of species through variation and natural selection, will now be dealt with. First, I want to point out an aspect that refers to the causal character of the most general laws of nature in the case of Whewell and Herschel (cf. point d, above). Already in the context of discovery Darwin speaks of natural selection as a 'force' (Ruse 1975, 172) and later repeatedly as a 'power' (Darwin 1964, 61, 410). The term *force* merely suggests what he had in fact explicitly explained in his *Notebooks*: Newton's force of gravitation achieves for celestial mechanics just the same as natural selection might for the organic world. Darwin's claim, seen against the background of the Herschel–Whewell methodology, is no less than to have discovered the *most general* law of the origin of species, as it can be described in terms of causality. He understands natural selection as *vera causa* (Darwin 1887, 2: 289n.). Preoccupied with this methodology, it is characteristic for the whole discussion that critics were well aware of Darwin's implicit claim (including the analogy to Newtonian celestial mechanics) and rejected it.[20]

Darwin himself contributed to this negative response, as he at first obviously did not realize that in contemporary physics gravitation had the status of a real entity, so he could therefore be charged with claiming the same for natural selection. This, however, was not Darwin's intention: he pointed out that the description of natural selection as a force was of a metaphorical kind, but he also maintained that Newton's force of gravitation could have no deeper meaning (Darwin 1876, 66). Both forces elude observation and the use of both finds justification only in making a large number of phenomena understandable by simple description. Against the *essentialism* of physicists Darwin directs their own preferential weapon, empiricist criticism, and insists on the descriptive function of theoretical expressions.[21]

The second important aspect of the specific criticism of Darwin concerns the variation of species. Darwin had described the occurrence of variations as 'due to chance' in the sense that he could not explain their origin, although he believed they were destined by laws of nature (Darwin 1876, 112, 138). That variation as a

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19 Cf. for instance Nagel 1971.

20 Cf. Hopkins 1973, 272.

21 Cf. Darwin 1887, 2: 286, 290. Ernst Mach, in his characteristic way, later reinterpreted this circumstance by taking into consideration Darwin's application of the Newtonian rule, i.e. 'to use only one actually observed cause (vera causa) for explanation' (Mach 1980, 177, note).

fundamental principle of evolution remained accidental in this sense was *unavoidable* for contemporary biology; for the 'general reader' it was *problematic* (Ellegård 1958); but for contemporary physics it was simply *unbearable*. Nearly all of Darwin's physicist critics emphasized this aspect: a theory of evolution that was based on an accidental principle could by no means be regarded as a *scientific* explanation at all. Victorian physics must have considered the term 'mechanism of evolution' as a *contradictio in adiecto*: a mechanism had to explicate the determinating circumstances of any individual case; this, however, does not apply to Darwin's doctrine.[22]

Later Darwin considered the objections against the doctrine as generally matter-of-fact and constructive (Darwin 1958, 125–26), but he was less positive on the criticism physicists had raised.[23] The question suggests itself as to which further reasons – beyond those of science and philosophy of science – could have motivated the vehement criticism of physicists. Here inevitably *theological* questions become involved. A comprehensive analysis of this aspect goes far beyond the scope of this contribution. It is, however, important to see the specific meaning that *physico-theology* had in Victorian physics (in contrast especially to the German tradition) in order to fully understand the reception of Darwin in that field.

The revelation of the most general and immutable laws of nature was regarded as the most noble aim of natural sciences also because it was assumed that thereby an intelligent design of creation could – so to speak – *inductively* be revealed and the existence of a creator God be proved. Newton among others supported this design argument, which was passed on by Derham, Paley, Whewell and others until the middle of the nineteenth century. To exaggerate, one might say that this argument was a canonical part of Victorian physics just like Newton's theory of

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22 For Herschel's criticism, see Hull 1995 and Hopkins 1973, 257–58, 267–68; Thomson 1891–94 2: 203–04; Stokes 1893, 41–53; Tait 1869 (albeit with a different argument); Jenkin 1973, 306–08 and (weak as regards content) Haughton 1973, 224–25. The criticism concerning accidental variation is closely related as well to physico-theological objections against Darwin (see below) as to the question of the duration of evolution (see part 3 of this chapter). The *argument of coincidence* leads directly to the *argument of probability*, according to which Darwin reflects on developments with statements of possibility and probability whereas the exact sciences claim certainty (see for instance Hopkins 1973, 257–58, 271–72). This argument, however, disappeared when in 1860 (at nearly the same time as the *Origin* was published) the development of statistical physics started with Maxwell's first study on the kinetic theory of gas. Charles S. Peirce seems to have been the first to realize that the integration of statements of probability into physics ran parallel to developments in biology (Peirce 1986, 244; see also Hull 1973, 33–34)

23 'On this standard of proof, natural science would never progress', he commented on Hopkins's review (Darwin 1887, 2: 315). He (rightly) regarded this review as 'a curiosity of unfairness and arrogance' (1903 1: 153). In Herschel's criticism he detected 'mockery' (1903 1: 330) – though admittedly inspired – and in Tait's discussion on the controversy concerning the age of the earth he found 'some good specimens of mathematical arrogance' (2: 314). After this controversy had started, Darwin generally warned of any confidence in the statements of physicists (2: 5, 313–14).

gravitation: especially Whewell, but also Herschel, Thomson, Stokes, Stewart and Tait, recognized it as an important argument against Darwin's idea of an undirected evolution.[24]

Newton's physico-theology is, however, not only concerned with the revelation of a divine design; it also allowed the possibility of divine intervention in the natural process. This concept could, however, no longer be maintained in physics – not after the success of the celestial mechanics of Laplace, who, as is well known, did not require the *hypothesis* of a God. But Victorian physics did not in consequence exclude any divine intervention in the living world of nature. It can rather be observed that physics increasingly regarded the concept of divine intervention as unscientific, whereas the organic realm became a kind of *reserve* for physicists where such intervention was still considered to be possible and necessary.[25]

In the same way as it is not justified to reduce criticism on Darwin from the physical sciences exclusively to theological convictions, objections from the philosophy of science cannot be regarded as mere instruments in the support of these convictions. Rather, guiding concepts of philosophy of science and physico-theology supported each other.[26] It would also be wrong to assume that the catalyst effect of the Darwinian doctrine had no impact at all on the physicists.[27]

It remains, however, to show that the reception of Darwin in the physical sciences was far more negative than that of the general reader. As the popular reception of Darwinism was also mainly influenced by religious convictions (Ellegård 1958), it is possible to understand this deviation by taking into account different *concepts of science*. Referring back to the quartet of characteristics described at the beginning for the physical sciences, Darwin's concept can be summarized as follows: it is *holistic* (metaphorically expressed: rather *netlike*

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24 In the sense that it was not only impossible to see a divine design in a process of evolution based on accidental variation and natural selection, but that such design was completely out of the question. 'I feel profoundly convinced that the argument from design has been greatly too much lost sight of in recent zoological speculations', notes for instance W. Thomson (1891–94, 2: 204). For further examples see Wilson 1974, 1989 (on Thomson and Stokes), Heimann 1972 (on Stewart and Tait) and Schweber 1989 (on Herschel). On Whewell's (wrong) criticism of Darwin in regard to the origin of life, see Hull 1995 and Young 1985, 144–45.

25 It would be therefore more precise to speak of the physicist's *bio-theology* instead of *physico-theology* – the latter term will, however, be mentioned as the established one and in a historical respect the more general one. The attitude of Stokes may in this context be quoted as typical (see Ellegård 1958, 83).

26 *Accidental* variation does not meet the standards of the philosophy of physics (see note 22); it did not express conformity to law but lawlessness. It could therefore not be integrated into the design argument: the God of Victorian physicists did not play dice.

27 Compare note 5. Herschel, Stokes and Thomson exemplify this point; on Herschel's later relativizing criticism see Hull 1995. Stokes and Thomson gave up their early creationist views and conceded at least a biological development of species, which was, however, directed by a vitalistic principle and did not therefore conform with Darwin's concept of evolution.

than pyramidal), it advocates for *probabilism* (aims at probability of statements instead of certainty), for *plausibilism* (claims for the comprehensibility of phenomena, not the prediction of new phenomena) and for *descriptionism* (it supplies description instead of genetic explanation in terms of causality). Physics itself had to revise its concept of science before it could adapt Darwin's doctrine. I will later come back to this aspect.

Darwin, W. Thomson, Helmholtz and the age of the earth

Criticism of Darwin by physicists was not restricted to objections of philosophy of science or physico-theology, but included points of contact between physics itself and the theory of evolution. The problem of the age of the earth played the most prominent role in this context.[28]

The discussion of this problem serves to illustrate the practical aspect of science in the relationship of physics and the theory of evolution. William Thomson has to be regarded as the foremost representative of Victorian physics, and Hermann von Helmholtz of German physics. A remarkable development has to be mentioned here in advance: in the eighteenth century the age of the earth was still estimated to be a few thousand years. In the middle of the nineteenth century geology and palaeontology immensely extended this period (Toulmin and Goodfield 1965). In his *Principles of Geology* (1830–33), Darwin's teacher Charles Lyell, the main representative of *uniformitarianism*, assumes almost *unlimited* periods of time for the history of the earth, without, however, committing himself to any figures.

For Darwin's idea of evolution by little and undirected steps, this development of geology meant a *conditio sine qua non*. In every edition of the *Origin* Darwin therefore gratefully refers to Lyell's *Principles* and emphasizes 'the incomprehensible length of former periods of earth'; on the basis of vague geological arguments he concludes that since the solidification of the earth 'far more than 300 million years' must have passed (Darwin 1964, 287).

From the side of physical science, J. B. Fourier had already examined the heat conduction of the earth and after that had treated the question of the age of the earth. But it was not until after the establishment of the second law of thermodynamics that the age of the sun–earth system became an interesting physical problem.

Physics inevitably got into conflict with geological uniformitarism, especially the thesis of a practically unlimited age for the earth. The gradual cooling of the earth and the limited supply of and dissipation of energy established in the second law, point as well to a limited supply of heat on earth in the future as compared to considerably higher temperatures of the earth in the past (and, related to these observations, to catastrophic geophysical changes of the earth's surface). Physics therefore had not only to limit the period of time for future life

28 Physical estimates of the age of the earth and (connected to that) the question about the age of the earth can be regarded as the historically best studied aspect of the subject. Details can therefore be omitted here; see Burchfield 1990, Brush 1979, Eiseley 1958, James 1982 and Sharlin 1972.

on earth (the well-known *heat death*), but also to limit the period in which the process of evolution had taken place. From today's point of view it is obvious that ignorance of radioactivity (as the source of energy of the sun and the interior of the earth) would lead physicists of the nineteenth century to estimates of the earth's age that were far too short in both directions. Interesting in this context are not these incorrect results (ascertainable only *post festum*), but the question of how Thomson and Helmholtz related them to Darwin's theory.

From 1852 and 1854 respectively, each worked independently on the source of the sun's energy, the change of its energy supply with passing time and possible consequences for the earth. Both agreed in stating – at least in the relevant period of time, that is from 1858 – that the heat of the sun could be explained by a contraction of its mass under the influence of gravitation.[29] Finally both arrived at similar estimates of the age of the earth.

Taking into account this similar theoretical background, it is astonishing in what completely different ways physical knowledge was marshalled with respect to the theory of evolution. As is well known, Thomson regarded Darwin's doctrine as scientifically unfounded and religiously suspicious; moreover, he was convinced of the 'total superfluousness of Darwin's philosophy' (Thompson 1910, 2: 637). It appears therefore to be no coincidence that Thomson established his first concrete estimates of the age of the earth shortly after the publication of the *Origin* and immediately used them to criticize Darwin. Thomson ascertained the probable age of the sun to be about 100 million years and suggested that the earth could not have been inhabited for longer than some 10 million years in view of the high temperatures of the solar system in early times: 'What then are we to think of such geological estimates as 300,000,000 years [. . .]?', he asked critically, with respect to the age of the earth that Darwin demands for evolution.[30] Thomson's estimates, however, were based on various ad hoc hypotheses and extrapolations which were not founded on empirical arguments and which were therefore subject to great variations.[31] For nearly forty years, starting in 1861, he nevertheless addressed the public with lectures and well-placed popular science essays on the age of the sun and the earth. Increasingly he refrained from revealing the hypothetical character of his

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29 Helmholtz supported the hypothesis of contraction as early as 1854 (Helmholtz 1896, 1: 80–82, 415–17; 2: 81–83). Thomson at first favoured the hypothesis of meteorites. After this was proven untenable he followed Helmholtz's explanation.

30 Thomson 1891–94, 1: 368; cf. 375. It can be assumed that Thomson adopted Helmholtz's hypothesis of contraction after the publication of the *Origin* (1859) to arm himself with physical objections against Darwin's estimates of the age of the earth (James 1982, 179). It is known that in 1861 he supported this hypothesis for the first time and used it against Darwin's own estimate (cf. note 33).

31 On Thomson's varying estimates, see Burchfield 1990; see also Pulte 1995, 124–25, for the continuation of this discussion. Also Fleeming Jenkin, who essentially supported Thomson's physical arguments against Darwin and popularized them in his famous review of the *Origin*, did at first not fundamentally exclude the possibility of new finite forms of energy being involved, but did not know that new energies could extend the age estimates in a way sufficient for Darwin. Jenkin, nevertheless, regarded his proof as self-evident (Jenkin 1973, 331).

estimates and emphasized their certain basis in the established laws of physics. As well as the preceding, which was by no means based on induction, a presentation on the popular science level was in no way compatible with Thomson's usual scientific activities (Sharlin 1972, 274ff.). This can only mean that for him there was more at stake than questions referring to physics: his aim was mainly a harsh criticism of Lyell's uniformitarianism and Darwin's theory of evolution. With respect to biology, he wanted to prove that the *actual* age of the earth (established by physical science) falsified Darwin's theory of an *open* evolution:

> The limitation of geological periods, imposed by physical science, cannot, of course, disprove the hypothesis of transmutation of species; but it does seem sufficient to disprove the doctrine that transmutation has taken place through 'descent with modification by natural selection'.[32]

In principle, Thomson accepted the origin of species through development. He believed, however, to have proved in physical terms that Darwin's undirected and therefore slow evolution had to be replaced by a principle that gave both direction and increased speed – a principle that corresponded to his physico-theology. He furthermore wanted to prevent those supporting Darwin from extending the process of evolution to the origin of *life*.[33]

Thomson's constant criticism attracted great attention within the sciences and among the interested public – not only because the initiator had been an undisputed authority in physics for more than half a century, but also because he was persistently supported by Stokes, Tait and Jenkin (Burchfield 1990).

Thus, controversy between physicists and Darwinian geologists and biologists was unavoidable. Inasmuch as physicists could not prove the assumptions of Thomson's estimates on the age of the earth, just as their opponents could not prove Thomson's figures wrong, the dispute also developed into a question of the *scientific quality* of the disciplines involved. As such, it represents the attitude that in the beginning was characterized as *physico-centrism*: Thomson, Tait and also Stokes claimed that *their* science, compared to the disciplines of natural history, was historically the more advanced one, that it was better grounded in

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32 Thomson 1891–94, 2: 89–90. Also in this conclusion Jenkin (see note 31) adhered to Thomson (Jenkin 1973, 327, 331).

33 Such natural explanation of the origin of life would have further extended the period of time required for evolution and was not acceptable for Thomson for religious reasons. Already in his first criticism of Darwin, in his lecture 'On the Age of the Sun's Heat' (1861, published 1862), it becomes clear that this concern motivates the continuation of his physical enquiries into the age of the sun and the earth (Thomson 1891–94 1: 357; cf. 422). Thomson (like Helmholtz) considers the possibility that earthly life could have been imported by meteors or other celestial bodies and defends this idea as 'not unscientific' (Thomson 1891–94, 2: 202–03; cf. Helmholtz 1896, 2: 89, 418–19). The evolutionary alternative, however, is compatible with his theistically based vitalism: 'I am ready to adopt, as an article of scientific faith, true through all space and through all time, that life proceeds from life and nothing but life' (Thomson 1891–94, 2: 199).

philosophy of science and that, consequently, their results on the age of the earth had to be acknowledged by geology and biology as assumptions.[34]

Thomson's examinations concerning the age of the earth and the sun reinforced most physicists' rejection of Darwin's theory. They also had an impact on biology: Darwin himself recognized that the question of the age of the earth involved the strongest objections against his theory (Darwin 1992, 385–86, 540). It was also the reason that Darwin's concept of evolution remained or once again became problematic with other biologists (Bowler 1990, 164). The discussion of the age of the earth therefore stimulated the search for mechanisms controlling evolution, that is, for undermining the central meaning of Darwin's theory according to its *modern* understanding.

Helmholtz, however, demonstrates that the retarding influence of physico-centrism was not inevitable: many parallels can be found in his and Thomson's research – both with respect to the question of age and to other fields. Their views on biology, however, differ in some important aspects. First, Helmholtz's physico-centrism implies a clearly expressed reductionism. The realm of the living is exclusively controlled by physical laws; *vitalism* is unacceptable for him.[35] His consequent demand, however, that it is 'the final aim of the natural sciences [. . .] to dissolve into mechanics'[36] can be regarded as an 'ideal claim' for the future, which at first had only scant consequences. Second, Helmholtz – who was trained to be a physician – does not have the slightest intention of claiming for physics a position of supremacy over biology in terms of methodology.[37] Third,

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[34] 'It is quite certain that a great mistake has been made – that British popular geology at the present time is in direct opposition to the principles of Natural Philosophy' (Thomson 1891–94, 2: 44; cf. 112–13). In his view, biology remains 'on a level of natural history' and finds its ideal in physics (197; cf. 10–11). Stokes regards it as indisputable that physical knowledge is superior to biological in terms of quantity but also – according to its evidence – in terms of quality: the Darwinian doctrine cannot cope with the 'severe demands for evidence that are required in the physical sciences' (Stokes 1883; for further information see Wilson 1987, 91). Tait finally uses the claim for exactness of mathematical physics in order to defend the superiority of Thomson's age estimates to those of geology: 'The fact is that . . . Mathematics is as essential an element of progress in every real science as language itself' (Tait 1869, 409). For further details, and for Huxley's witty criticism of this argument, see Burchfield 1990, 84–86.

[35] Cf. note 33 on Thomson's vitalism. Helmholtz's main objection against vitalism is the argument that the introduction of a 'life force' would violate the principle of conservation of energy – in the establishment of which he himself took part (Helmholtz 1896, 1: 386–89; and vol. 2).

[36] '[. . .] das Endziel der Naturwissenschaften ist, die allen anderen Veränderungen zu Grunde liegenden Bewegungen und deren Triebkräfte zu finden, also sich in Mechanik aufzulösen' (Helmholtz 1896, 1: 396).

[37] Helmholtz does not regard the relationship between the sciences in a hierarchical way like Thomson (cf. note 34). He rather sees it as characterized by processes of fruitful rewarding exchange, made necessary by specialization and division of labour. Any dogmatism (in respect to metaphysics or methodology) would impede them (Helmholtz 1896, 1: 159–70). In his discussions on methodology he indeed supports 'the strict discipline of the inductive method' and defends the inductivism

Helmholtz rejects any teleological explanations as well of the animate as the inanimate nature. For example, in his later studies on theoretical physics he attempted to establish the principle of least action (suspicious in physico-theological terms) as the most general law of nature – without taking over any metaphysical legacy. He avoids by any means the impression that in physical processes there was an immanent progression towards an aim or any higher providence at work. The mechanistic interpretation of this principle is therefore of special meaning to Helmholtz.[38] By analogy, he does not regard the obvious functionalism, for instance in the building of organs, as an issue of proof in the sense of physico-theology, but rather as a problem that needed to be explained by the sciences.

Against this background it can be understood that Helmholtz's assessment of the theory of evolution was quite different from Thomson's, because the former found in Darwin's doctrine not a threat to theological convictions, but an important contribution to carrying out his own, mechanistic programme. In Helmholtz's view, the main merit of the theory of evolution is to further the natural (i.e. neither physico-theological nor vitalistic) explanation of anything that *seems* purposeful in nature: 'Darwin's theory contains an essential new creative thought. It demonstrates how, for instance, appropriateness of formation in any organism can occur without any inference of intelligence through the blind working of a natural law.'[39] Helmholtz regards this theory not as a complete one, but as a theory of natural science with great force of explanation increasingly improved in terms of evidence.[40]

How did Helmholtz combine this theory with physical estimates of the age of the earth? He agreed in principle with Thomson's estimates and was without doubt aware of the 'direct contradiction' Thomson establishes with respect to

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of British physicists against Zöllner's polemic (Helmholtz 2: 413–21; cf. also 432–34). However, the attribute *inductive* in Helmholtz is not to be understood in the sense of a hierarchical-gradualistic theory, but in a weaker sense as *empirically based*. See Pulte 1995, 128–29 for further implications with respect to Darwin.

38 On the history of this principle and its physico-theological implications, see Pulte 1989.

39 'Darwin's Theorie enthält einen wesentlich neuen schöpferischen Gedanken. Sie zeigt, wie Zweckmässigkeit der Bildung in den Organismen auch ohne alle Einmischung von Intelligenz durch das blinde Walten eines Naturgesetzes entstehen kann' (Helmholtz 1896, 1: 388). Of course, the question arises of how Helmholtz integrates the accidental nature of Darwinian variation (cf. note 22) within his mechanism. His explanations of the 'law of heredity of individual peculiarities from parent to child' lack any comment on this problem. In the context of Helmholtz's mechanism, this can only be a matter of provisional chance (in the sense Darwin had outlined) that had to be eliminated by a mechanistic law, or governed process, in the future.

40 As early as 1869 Helmholtz remarks that the explanatory power of his theory is not only to be found in its *organizing* function, but also in its *prognostic* function – in the sense of predicting retrospectively how gaps in Darwin's lines of development can be filled (Helmholtz 1896, 1: 389).

geology and the theory of evolution.[41] However, he himself did not make this supposed contradiction explicit. Rather he pointed out how incomplete the biological and physical understanding of the beginning and end of the earth was, and he emphasized that the problem was open to further study (Helmholtz 1896, 2: 88–89). He used the idea of adaptation to existing geological and physical surroundings in order to extend the period of time that physics thought possible for earthly life.[42] To sum up: where Thomson finds irreconcilable contradiction, Helmholtz harmonizes and refers to future clarification.

Thomson and Helmholtz demonstrate to what extent philosophical and theological background convictions can influence practical research and define strategies of scientific research: for example, the thesis about the physical age of the earth – in no way certain according to scientific standards – persistently pursued and used – summoning up the whole authority of the subject – as a hard argument against a theory that contradicts these concepts (Thomson). The *same thesis* can also be devalued to a *hypothesis*, a soft assumption in order to support a new theory regarded as fruitful and in agreement with one's own conceptions (Helmholtz). In the context of their particular philosophy of science, Thomson's as well as Helmholtz's attitude towards Darwin's theory can be judged as rationally founded and only *post festum* can Helmholtz's position be characterized as the more suitable.

The more influential position anyway was that of Victorian physicists. Generally, the theory of the age of the earth demonstrates that an established and dominant science like physics can – for a long time and without being right – handicap developments in another discipline, like that of biology (again, judged *post festum*). This dominating variation of physico-centrism had clearly negative effects on Darwin.

The theory of evolution in the nineteenth century was in fact not capable of translating *its* age of the earth from premises (given by geology) into an explanation (maintained against physics). It was physics itself which by means of revolutionary changes of its own foundations, like for example the discovery of natural radioactivity, came to an enormous extension of the age of the earth. Physics *itself* eliminated the contradiction with which it had charged Darwinian theory.

Ernst Mach's 'Copernican Revolution' of physico-centrism

Tyndall and Helmholtz did not join the general physicists' front against Darwin. Both saw the possibility of integrating the theory of evolution into their own

41 According to Helmholtz's own calculation the gravitation contraction of the sun would have sufficed 'to cover with its present heat release not less than 22 million years in the past'. Projected into the future '17 million more years of sunshine of the same intensity [would be] maintained, which is now the source of all earthly life' (Helmholtz 1896, 1: 86–87). Helmholtz had excellent contacts with other British physicists, Thomson among them. He visited Britain several times to attend lectures and conferences, as in 1861 when the controversy on the age of the earth started (Königsberger 1902–03, esp. 1: 372–74). His good relations with e.g. Thomson and Tait make it perfectly understandable why Helmholtz did not take part in this debate.

42 Cf. Helmholtz 1896, 2: esp. 89.

mechanistic programmes. They did, however, not draw a conclusion that suggests itself if the idea of evolution is consequently applied to man as cognitive subject (i.e. at the same time also as object): that human cognitive structures and therefore also the laws of physics could be understood as products of adaptation to a certain (perhaps mesocosmic) part of reality. These laws could therefore claim only limited validity (for just this part) and had to be regarded as being subject to changes in time. The new mechanism of Tyndall and Helmholtz adheres in contrast and in spite of all differences to the traditional mechanism of an essentialistic concept of law that finds universal and unchangeable laws of nature in the outward reality, which confront man as 'real power'.[43]

For Ernst Mach, on the other hand, the causal lawfulness in question only *appears* as a 'strange power'.[44] He regards such a mechanism as only a historically conceivable 'prejudice' (Mach 1982, 472) that he himself got rid of quite early. A few years after the publication of the *Origin*, he was the first representative of the exact sciences, who – starting from Darwin's doctrine – tried to make the theory of knowledge and philosophy of science benefit from the idea of development.[45] This inevitably means a rejection of physico-centrism – a Copernican Revolution, so to speak, in the relationship between physics and biology. In the case of Mach it is appropriate to speak of an idea of development (*Entwicklung*) imported by Darwin, and not of a concept of evolution in the strict Darwinian sense. This idea establishes an *organic* context for all areas of his scientific thought which, in the following passage, will be outlined in its different aspects: biology, theory of knowledge and philosophy of science.

In the context of *biology* Mach refers nearly exclusively to Darwin and mentions Lamarck only sporadically as forerunner, although he attaches great importance to Lamarck's idea of the inheritance of acquired characteristics.[46]

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43 'So tritt uns das Gesetz als eine objective Macht entgegen, und demgemäss nennen wir es *Kraft*' (Helmholtz 1896, 1: 376). This view is not affected by the change of his conception of science (cf. Helmholtz 1922, 14). Only when he considers the status of the axioms of geometry does he deal with cognitive structure and adaptation (Helmholtz 1896, 2: 15). On Tyndall, cf. note 13 above.

44 'Der Glaube an die geheimnisvolle Macht, *Kausalität* genannt, welche Gedanken und Tatsachen in Übereinstimmung hält, wird aber bei dem sehr erschüttert, der zum erstenmal ein neues Erfahrungsgebiet betritt' (Mach 1923, 252).

45 In 1863, Mach still represents mechanism, especially an essentialistic concept of law in the science of Helmholtz (Mach 1863, 3–8). The theory of evolution was obviously an important moment to cancel this position. In retrospect Mach wrote: 'I got to know Lamarck's doctrine as early as 1854. [I] was therefore well prepared to learn Darwin's ideas. They became effective already in my Graz lectures 1864–67 and are expressed in the concept of a competition of scientific thoughts as struggle for life, as survival of the most suitable' (Mach 1910, 600). Mach's casual transition from Lamarck to Darwin for the first time makes it clear that he did not principally differentiate between the two approaches.

46 See Mach 1923, 246; Mach 1919, 380–81; and for the heredity of acquired characteristics, Mach 1923, 615; Mach 1991, 64–65. In contrast to Weismann's rigorous biological criticism of this Lamarckian concept, Mach at least insists on the possibility that 'the influence of individual life on descendants cannot be excluded' (Mach 1991, 65; cf. Mach 1923, 615).

The theory of evolution is often referred to in support of the concept of development, but its biological statements are *nowhere* discussed in detail. Mach obviously does not principally reflect and definitely not accept especially the accidental character of variation and the aimlessness of evolution.[47]

With respect to the biological content of the Darwinian theory we find an *uncertainty relation* in Mach[48] which proves essential for the application of this doctrine to the *theory of knowledge*:[49] 'cognition is an expression of organic nature'.[50] This dictum could be described as the *basic principle* of his doctrine of knowledge: Mach actually wants to make all forms of cognition ranging from the simple memory performance of an animal to a general scientific idea and cultural creation understandable as an achievement of the adaptation of individual and race in the struggle for survival: 'Thoughts are not "separate" beings. But thoughts are expressions of organic life. And, if Darwin had the right view, the trait of reorganisation and development must be realized in it.'[51] To a large extent Mach's doctrine of knowledge can be comprehended as an explanation of this thought: 'Expressed briefly, the task of scientific condition appears then as follows: the adaptation of thoughts to facts and the adaptation of thoughts to each other.'[52]

Mach himself spoke of the problem so as to comprehend 'the whole technical and scientific culture as [. . .] a detour' with the aim of self-preservation.[53] An answer to this problem is his use of the term *evolution* in the cognitive-cultural field: in respect to the *uncertainty* that arises in the biological context he definitely decides *against* the Darwinian concept of development. Mach believes that the accumulated knowledge of an individual gets biologically inscribed and is passed on to any descendants. As far as the comprehension of cognitive changes in the widest sense is concerned, his concept of development is strongly influenced by

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47 Cf. Mach 1923, 247, 287; see Pulte 1995, 133–34 for further details.

48 This uncertainty is also expressed in his undecided judgement of Darwinian theory: he declares it as equally important as Galileo's mechanics (Mach 1919, 380–81; Mach 1923, 247–48) and states at the same time that he regards 'the doctrine of development in any form as a modifiable, intensifiable working hypothesis of natural sciences' (Mach 1991, 65–66).

49 Mach merely speaks of a 'doctrine of knowledge' to deliberately differentiate himself from traditional systems of philosophy and describes this doctrine as a 'biological-economic' one (Mach 1910, 600) to make clear that Darwinian biology and political economy decisively influenced even the 'ontogenesis' of his views; cf. Čapek 1968.

50 'die Erkenntnis ist eine Äußerung der organischen Natur' (Mach 1923, 249).

51 'Gedanken sind keine *gesonderten* Lebewesen. Doch sind Gedanken Aeusserungen des organischen Lebens. Und, wenn Darwin einen richtigen Blick getroffen hat, muss der Zug der Umbildung und Entwicklung an denselben wahrzunehmen sein' (Mach 1919, 382).

52 'In kürzester Art ausgedrückt erscheint dann als Aufgabe der wissenschaftlichen Erkenntnis: Die Anpassung der Gedanken an die Tatsachen und die Anpassung der Gedanken aneinander' (Mach 1910, 600; cf. Mach 1923, 590, 227–30).

53 'Die ganze technische und wissenschaftliche Kultur kann als ein solcher Umweg angesehen werden' (Mach 1980, 60).

Lamarck.[54] For Mach, the process of cognitive development of any individual and the race is decisively defined by *progress*.[55] In contrast to his own assessment, it is Lamarck's biological model rather than Darwin's standard view – with respect to cognitive developments he has a certain concept of progress (Engels 1989, 83) – that corresponds with his ideas on the dynamics of science.

To see this is important especially with respect to his historiography of science,[56] whereas Darwin's idea of biological orientation is decisive for his philosophy of science in the stricter sense. In spite of his basically empiricist attitude, Mach here arrives at a view that has little in common with that of the older inductivism, according to which 'discovery was a quite comfortable craft' (Mach 1919, 445). There are, on the other hand, important aspects in which Mach agrees with Darwin's concept of science. Considered in the context of the earlier characterizations (above), Mach's concept can be summed up as follows: (1) it includes Darwin's rather *holistic* concept of theory,[57] and it advocates for (2) *probabilism* (and not certism), (3) *plausibilism* (and not prognosticism)[58] and (4) *descriptionism* (and not essentialism).

Therefore, none of the objections based on philosophy of science that were expressed by Victorian physicists against Darwin were of any relevance to Mach. Neither did *physico-centrism* (even the affirmative character of Helmholtz's) have any impact. The traditional physicist's view of the relationship between physics and biology, outlined before, is not exactly inverted by Mach, because developmental biology can only teach physics that its basic premises (like the structure of space and time and the principle of causality) were historically developed and therefore changeable, but could not show *how* this change looked. However, physics and biology are to a certain extent brought into *balance*. Mach's axiom – 'Science does not produce a fact out of another but it arranges the known [facts]'[59] – is fulfilled by the Darwinian theory of evolution as well as by theoretical mechanics or electrodynamics. Neither for Whewell nor for William

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54 See especially Mach 1923, 615–17. Mach actually believes that 'basic organic developments' could explain why new scientific theories were rejected at first but 'after a few centuries generally were accepted (Mach 1923, 258).

55 There is enough evidence (see Mach 1923, 257–65) for the view that Mach did not share Darwin's 'ambiguous attitude towards progress' (Engels 1989, 89). This becomes evident in his idea of the 'just' progress of the history of science (Mach 1923, 76).

56 Mach is a good example for demonstrating that theories of history of science which consider recorded historical processes cannot refer to Darwin's theory of evolution – and vice versa (Bayertz 1987). Especially in respect to the accidental variation of biology there is no even approximately satisfying analogy in the realm of the genesis of ideas or theories. It has therefore a certain symbolic meaning when Mach at the end of his life inverts the early development 'of Lamarck to Darwin': 'I intend [. . .] to change, that is to revert [. . .] my position between Darwin and Lamarck; I think now that Lamarck has the more astute mind' (Blackmore and Hentschel 1985, 142; cf. 146f.).

57 Cf. note 18; see Mach 1980, 165, 202–03 and Pulte 1995, 136–37, for more details.

58 Cf. Mach 1923, 283–84, with special attention to natural history.

59 'Die Wissenschaft schafft nicht eine Tatsache aus der anderen, sie ordnet aber die bekannten' (Mach 1923, 242).

Thomson would this consequence be acceptable in terms of their philosophy of science, and Helmholtz avoids it as well. However, when Mach concludes that 'The most impressive laws of physics – dissolved into their elements – do in no way differ from the descriptive sentences of the natural historian',[60] he is *also* referring to Darwin, and he would not have drawn this conclusion *without* Darwin.

Concluding remarks

Mach's reception of Darwin, like his philosophy of science in general, had enormous influence on the physics of the closing years of the nineteenth and the early twentieth centuries. Presumably more than any other physicist he contributed to the introduction of Darwinian ideas into scientific and technical education in the German-speaking lands.[61] Ludwig Boltzmann, Mach's (informal) successor in Vienna and his opponent in the controversy over atomism, most likely became a supporter of Darwin's theory of evolution because of him. Boltzmann predicted that the nineteenth century would one day be celebrated as the 'century of a mechanistic concept of nature, the century of Darwin'.[62]

Among nineteenth-century German physicists Helmholtz, Mach and Boltzmann were also the guiding intellectual forces in the philosophy of science. Their examples of positive reception of Darwin are in strong contrast to his reception in Victorian physics; a closer examination of the German reception would probably confirm this outcome. Therefore, it will be necessary to look for aspects on different levels of the complex reception of Darwin, which made the more positive reception in German physics possible. A few preliminary ideas on this problem will close this chapter.

In Germany, biology seems to have been more established on an institutional level and its relation to physics closer and less burdened with institutional and curricular restrictions. Research in an adjacent field like sense physiology was thus made easier (Helmholtz, Mach, Fechner, Zöllner, etc.; cf. Helmholtz 1896, 1: 396–97) and contributed to the gradual removal of physico-centrism. Mach's example in this context is representative, but a reductionist like Helmholtz also saw the chance to make mechanism and the theory of evolution compatible.

Second, under the influence of German academic philosophy, it was doubtless the mid-century debate on materialism that helped prepare a positive reception of Darwin (Gregory 1977, 164ff.). Tyndall's scientific materialism in Great

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60 'Die imposantesten Sätze der Physik, lösen wir sie in ihre Elemente auf, unterscheiden sich in nichts von den beschreibenden Sätzen des Naturhistorikers' (Mach 1923, 230).

61 On the problematic character of the term *scientific Darwinism* see notes 55 and 56. A remarkable example of Mach's impact is August Föppl (see, for example, Föppl 1925, 25) and his own, extremely influential role in spreading Darwinian ideas. See Pulte 1995, 137–38, for details.

62 'Wenn Sie nach meiner innersten Überzeugung fragen, ob man es einmal das eiserne Jahrhundert oder das Jahrhundert des Dampfes oder der Elektrizität nennen wird, so antworte ich ohne Bedenken, das Jahrhundert der mechanischen Naturauffassung, das Jahrhundert Darwins wird es heißen' (Boltzmann 1905, 28).

Britain developed later and did not serve as a forerunner, but rather as a companion of Darwinism.

Third, the physico-theological design argument was of crucial importance to Darwin's critics among Victorian physicists. In German physics of the nineteenth century, however, physico-theology had become unimportant – a fact that has to be considered in the context of the history of the philosophy, especially of Kant's very influential criticism of teleology.

Finally, the fact that a rather rigid inductivism was the leading methodology of science of Victorian physics had a negative impact on Darwin's reception. German-speaking physics did not have such a dominant theory of science. Yet it can generally be stated that more scope was permitted in Germany for the development of scientific theories that were not inductively established in the sense of Herschel or Whewell. It is characteristic that at the end of the century the Darwin-supporter Boltzmann found his kinetic theory of gas criticized with similar objections to those the Darwin-opponents Tait, Thomson and others had expressed against Darwin's theory before (Bellone 1980, 29ff.).

Although Darwin's theory of evolution at first had to assert itself against the vehement rejection of Victorian physicists, other examples, like Mach and Boltzmann for physics, and Clifford and Poincaré for mathematics, demonstrate how strongly the theory of evolution *in the long run* influenced the self-image of the so-called exact sciences and contributed to making their concept of science *dynamic*. Further research is necessary to understand this process in detail and to assess its contribution to the development of a *modern* concept of science. As Mach himself recognized: 'Darwin's ideas are too important and far-reaching not to have an influence on all fields of knowledge.'[63]

63 'Darwin's Gedanke ist eben zu bedeutend und weittragend, um nicht auf alle Wissensgebiete Einfluss zu nehmen' (Mach 1919, 360).