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NIELS BOHR'S ARGUMENT FOR THE IRREDUCIBILITY OF BIOLOGY TO PHYSICS

1. INTRODUCTION

Even in his youth, Bohr was familiar with those difficult and controversial questions surrounding the relationship of the phenomena of life to those of inanimate nature, or in other words, the relationship of biology to physics and chemistry. (See *e.g.*, *APHK*, 96; Folse, 1985, 45–46; and 1990a, 212; Holton, 1970, 142–143, 151; Kay, 1985a, 490; Meyer-Abich, 1965, 180; Petersen, 1985, 307; and Röseberg, 1985, 15–18, 195–196.) Are the phenomena of life in any sense fundamentally different from the processes of inanimate nature, or aren't they? Bohr became more intensely preoccupied with this question once the stormy development of quantum mechanics had more or less wound down.

The first published evidence of this renewed interest may be found in Bohr's written elaboration of an address delivered in 1929, entitled "The Atomic Theory and the Fundamental Principles Underlying the Description of Nature" (Bohr, 1929). Here, however, Bohr takes no stand on whether or not biology may ultimately be captured by physics. Indeed, nothing in this text unequivocally indicates that Bohr even takes this question seriously. While, in the last paragraph of this essay, Bohr argues that quantum theory will surely have to be adduced in the explanation of certain biological phenomena, such as sense-perception under low-intensity stimulus conditions, nothing precludes the possibility that, for certain other biological processes, such as blood circulation or the conduction of nerve-impulses, chemistry and classical physics alone will suffice. However, this possibility is open only "to account for those effects which first call for our consideration" (*ATDN*, 118). If, on the other hand, we wish to go beyond these "effects which first call for our attention" aiming instead at an understanding of the role of the phenomena in question within the organism as a whole, the situation changes, as Bohr explains immediately following the passage cited above:

> With regard to the more profound biological problems, however, in which we are concerned with the freedom and power of adaptation of the organism in its reaction to external stimuli, we must expect to find that the recognition of relationships of wider scope will require that the same conditions be taken into consideration which determine the limitation of the causal mode of description in the case of atomic phenomena. (*ATDN*, 118–9)

J. Faye and H. J. Folse (eds.), Niels Bohr and Contemporary Philosophy, 231–255.

What does Bohr mean by "the same conditions be taken into consideration which determine the limitation of the causal mode of description in the case of atomic phenomena"? The present context suggests, quite naturally, that he is alluding to quantum theory (and the complementarity peculiar to that theory). For now, there is no hint of a second level of constraint, above and beyond the constraint of classical description by the quantum theory: the constraint of quantum-mechanical description in light of the "more profound problems of biology".[1]

Things look rather different, however, in the "Introductory Survey", written in 1929, to Bohr's *Atomic Theory and the Description of Nature*,[2] in which the aforementioned lecture is published. Here Bohr writes,

> Nevertheless, it is obviously a quite open question whether the information we have acquired of the laws describing atomic phenomena provides us with a sufficient basis for tackling the problem of living organisms, or whether, hidden behind the riddle of life, there lie yet unexplored aspects of epistemology. (*ATDN*, 21)

Here the adequacy of quantum-mechanics in the description of living organisms is characterized as "a quite open question"; the two options are clearly seen and acknowledged. In addition, Bohr suggests that the inadequacy of quantum mechanics could lead to a revolutionary development of a magnitude comparable to that of the quantum-mechanical revolution itself.

By 1931, Bohr had made a fairly firm decision for one of these options. He takes up the topic in his 1931 "Addendum" to the "Introductory Survey", where he claims that

> ...the lessons we have learned by the discovery of the quantum of action open up to us new prospects which may perhaps be of decisive importance, particularly in the discussion of the position of *living organisms* in our picture of the world. (*ATDN*, 22)

These "new prospects" arise out of the likelihood that physics alone won't be enough to capture life: "...even the quantum mechanics may hardly depart sufficiently from the mode of description of classical mechanics to be capable of mastering the characteristic laws of life" (*ATDN*, 22). Bohr justifies his conjecture that quantum mechanics is probably insufficient for the explanation of the phenomena of life by the further claim that

> ...quantum mechanics is concerned with the statistical behaviour of *a given number* of atoms under *well-defined* external conditions, while we are unable to define the state of a living being in terms of atomic measures; in fact, owing to the metabolism of the organism, it is not even possible to ascertain what atoms actually belong to the living individual. (*ATDN*, 23; emphasis mine)

This argument has two parts. First, Bohr claims that quantum mechanics is a theory of *closed* systems, while living organisms are *open* systems. In addition, the proper application of quantum mechanics requires that we determine an initial state for the system. The definition of an initial state requires "an observation . . . as complete as possible from the point of view of the atomic theory" (*ATDN*, 22); or, put slightly differently, an observation which determines the state of the individual atoms within the limits allowed by the uncertainty principle. But the need for such observation sets

> . . . a fundamental limit to the analysis of the phenomena of life in terms of physical concepts, since the interference necessitated by an observation which would be as complete as possible from the point of view of the atomic theory would cause the *death of the organism*. (*ATDN*, 22, emphasis mine)

In other words, the phenomenon under study is incompatible with the necessary conditions for the applicability of the relevant physical concepts. Bohr formulates this point as follows: "*the strict application of those concepts which are adapted to our description of inanimate nature might stand in a relationship of exclusion to the consideration of the laws of the phenomena of life*" (*ATDN*, 22–23, original emphasis). This incompatibility is analogous to a situation which arises in quantum mechanics, a situation in which the notion of complementarity comes into play:

> In exactly the same way as it is only possible on the basis of the fundamental complementarity between the applicability of the concept of atomic states and the coordination of the atomic particles in space and time to account, in a rational manner, for the characteristic stability of the properties of atoms, so might the peculiarity of the phenomena of life, and in particular the self-stabilizing power of organisms, be inseparably connected with the fundamental impossibility of a detailed analysis of the physical conditions under which life takes place. (*ATDN*, 23)

This argument, presented in one scant page of Bohr's "Addendum", is given a more thorough exposition in the famous 1932 lecture, 'Light and Life', with emphasis on the second part of the argument, which invokes the notion of complementarity. I will consider the argument as it is presented there in greater detail. First, however, I shall canvass some of the influence this lecture has had in subsequent years, noting along the way a certain irony.

In 1931, the young physicist Max Delbrück, who the previous year had completed his dissertation at Göttingen under Max Born, began his six-month tenure as a Rockefeller Fellow at Bohr's institute in Copenhagen (Fischer, 1985, 11; Kay, 1985a, 490; and 1985b, 213; and Stent, 1989, 12). At the time, Bohr was concerned with the consequences of complementarity for biology, among other issues. At that point, young Delbrück held biology to be a discipline of few intellectual challenges (compare Kay 1985a, 490). Nor was it his discussions with Bohr on the extension of complementarity to encompass the relationship between physics and biology which moved Delbrück to make biology his own field of study; the analogy asserted by Bohr struck him as too vague. It took Bohr's lecture 'Light and Life' before Delbrück would give up atomic and nuclear physics, ultimately devoting himself entirely to biology (*Essays*, 23; Delbrück, 1949, 22; Fischer, 1985, 69–71; Kay, 1985a, 492, 494; and 1985b, 214–215; Rosenfeld, 1967, 134; Stent, 1968, 393; and 1989, 12–13).

The intellectual challenge arising out of Bohr's diagnosis of the complementary relationship between physics and biology was the task of finding laws characteristic of living matter which, in principle, must resist all explanation on the basis of known physics and chemistry. Delbrück's first work in biology came about in cooperation with the geneticist N.V. Timoféeff-Ressovsky, then division head at Berlin's Kaiser-Wilhelm-Institut, and his physicist associate K.G. Zimmer (Delbrück, 1935; Fischer, 1985, 75–81; Kay, 1985b, 219–221). The resulting paper would prove highly influential. Though initially it received little notice, it helped Delbrück to institutionalize his own program of research in phage genetics at Caltech (Fischer, 1985, 81ff.; and Winkler 1985, 546–547).[3] It became widely known only through Erwin Schrödinger's 1944 book, *What is Life?*, based in large part on Delbrück's views regarding the nature of genes, which Schrödinger called "Delbrück's Model" (Schrödinger, 1944, 47, 60, 71, and elsewhere). Schrödinger's book had an extraordinary influence on the development of molecular biology as an academic discipline, since it presented fundamental biological problems in a manner palatable to physicists (Fischer, 1985, 135; see Fischer's further references; Kay, 1985a, 501 and 1985b, 242–243; Stent, 1966, 3–4; and 1968, 392; Winkler, 1985, 545). The research tradition which began, inspired by Bohr's 'Light and Life', with Delbrück's 1935 paper, ultimately gave rise to Watson and Crick's 1953 discovery of the structure of DNA (Watson and Crick, 1953).[4] But now the double helix structure of DNA made it clear that one key biological process, that of genetic replication, could be understood entirely on the basis of known physics – a conclusion in sharp contrast to the original intention of Delbrück's program (compare Kay, 1985b, 244).

"Light and Life", which provided the initial impetus for this program, was delivered as an opening address for the International Congress on Light Therapy in Copenhagen, on August 15, 1932, and in 1933 was published, in English, in the congress proceedings. A Danish version differing from this only "by some formal alterations"[5] also appeared in 1933, in *Naturens Verden*, and corresponding English and German versions were published in

Nature and *Die Naturwissenschaften* the same year, making the essay accessible to a very wide audience.

As Bohr puts it in the introductory paragraph of this lecture or essay, his leading question is "... the problem of what significance the results reached in the limited domain of physics may have for our views on the position of living organisms in the realm of natural science" (Bohr, 1933, 421). For Bohr, the physical result of primary interest is "the discovery of an essential limitation of the mechanical description of natural phenomena" (*Idem*), a limitation which first became manifest in the study of light. This limitation in the mechanical description of nature consists in the fact that the phenomena of light have "features that cannot be brought into conformity with the demands hitherto made [*i.e.* by classical physics] to a physical explanation" (*Idem*). Such results, of initial interest only to physics, are relevant to biology because of an analogy between light and life. In consequence of this analogy, biology is irreducible to, but may never be allowed to contradict physics. The explication of this analogy and its consequences constitute the body of Bohr's essay.

But before we can explore Bohr's argument for the irreducibility of biology to physics in detail, we must ask what, precisely, Bohr's anti-reductionist claim asserts. The concept of a reduction is notoriously heterogeneous, and accordingly, claims of reducibility or irreducibility may have a variety of meanings (compare *e.g.* Hoyningen-Huene, 1985). The anti-reductionist claim peculiar to Bohr's 'Light and Life' is explicated in section 2. In section 3 Bohr's argument for this claim is reconstructed, and in section 4 the argument is subjected to critical discussion.[6]

2. THE ANTI-REDUCTIONIST CLAIM

After arguing the relevance of quantum mechanics in the explanation of the special features of living organisms, "Light and Life" proceeds to its real topic as follows:

> The recognition of the essential importance of fundamentally atomistic features in the functions of living organisms is by no means sufficient ... for a comprehensive explanation of biological phenomena. The *question* at issue, therefore, is whether some fundamental traits are still missing in the analysis of natural phenomena, before we can reach an understanding of life on the basis of physical experience. (Bohr, 1933, 457, emphasis mine)

What the second sentence of this passage terms a *question* is taken up, at the end of the following paragraph, as a *claim*, as "the asserted impossibility of a physical or chemical explanation of the functions peculiar to life" (*Ibid.*, 458). Similarly, in the concluding section, Bohr talks about "the necessary renunciation as regards an explanation of life" (*Ibid.*, 459); as is clear from the context, Bohr is talking about the physico-chemical explanation of life. The central anti-reductionist claim of 'Light and Life' is thus as follows: *Life, or more precisely, the functions peculiar to life, cannot be explained by means of physics and chemistry alone*. In 2.1, I shall analyse the key concepts in Bohr's claim, and in 2.2 I shall relate Bohr's anti-reductionist claim to forms of anti-reductionism familiar from discussions in the philosophy of science.

2.1. *Explication of Concepts*

Three questions must be asked regarding the concepts which figure in Bohr's assertion of the "impossibility of a physical or chemical explanation of the functions peculiar to life":

1. What does Bohr mean by "functions peculiar to life"?
2. What, precisely, is a *physical or chemical explanation*?
3. In what sense is a physical or chemical explanation of relevant functions of life supposed to be *impossible*?

Regarding 1: What does Bohr mean by "*functions peculiar to life*"? Bohr delimits the domain of phenomena he believes are inexplicable by physics or chemistry by examples. We find him speaking of "such characteristic biological phenomena as the self-preservation and the propagation of individuals" (*Ibid.*, 458).[7] Bohr characterizes the realm of such phenomena as one in which "the concept of purpose, which is foreign to mechanical analysis, finds a certain field of application in problems where regard must be taken of the nature of life" (*Idem*). These examples are sufficient to clearly delimit the domain Bohr has in view: functions peculiar to life are those phenomena typically witnessed in living organisms, and only in living organisms, such as their tendency toward self-preservation and propagation.

Regarding 2: What, precisely, is a *physical or chemical explanation*? At the beginning of 'Light and Life', Bohr asserts that, in general, "any scientific explanation necessarily must consist in reducing the description of more complex phenomena to that of simpler ones" (*Ibid.*, 421). As explanatorily potent simple phenomena, Bohr especially has in mind those described by the *ontological assertions* contained within general theories, where 'ontological assertions' shall refer to those assertions a theory makes about the existence or essential attributes of the entities which make up a given domain of phenomena. This interpretation is supported, for example, by Bohr's claim that light "finds a simple *explanation* in the electromagnetic *theory*" (*Ibid.*, 421, emphasis mine). That Bohr took a theory's ontological assertions as fundamental to such explanation emerges from the following passage:

> The *idea of the wave nature of light* . . . not only forms the *basis for our explanation* of the colour phenomena . . . but is also of essential importance for every detailed analysis of optical phenomena. As a typical example, I need only mention . . . interference patterns. (*Ibid.*, 421, emphasis mine)

If we follow this interpretation, the envisaged explanation of peculiarly biological phenomena would trace them back to chemical and physical theories, and the ontological assertions they entail. One cannot help but notice, however, that Bohr's lecture barely acknowledges chemistry as an independent source of theories and ontological assertions. In fact, the aforementioned passage in which Bohr talks of the "impossibility of a physical *or chemical* explanation" (*Ibid.*, 458, emphasis mine) is the *only* instance in the entire lecture in which chemistry appears in this context. Elsewhere, Bohr simply talks of physics, without mentioning chemistry at all. The reason for this omission is that, for Bohr, the to a large extent successfully completed program of atomic physics is the reduction of chemistry to physics. For instance, in the 1932 published version of his Faraday Lecture, "Chemistry and the Quantum Theory of Atomic Constitution", delivered in May, 1930, at the Chemical Society in London, Bohr writes ". . . we have even gained detailed information regarding the structure of atoms, which to a wide extent allows us to interpret the properties of the chemical elements as consequences of general physical laws" (Bohr, 1932, 349).[8] It follows that "all sharp distinction is now disappearing [between physics and chemistry] on account of the rapid growth of our insight into the atomic constitution of matter" (*Ibid.*)[9] In other words, as far as the task of tracing back biological phenomena to "simpler phenomena" is concerned, Bohr doesn't view chemistry as a discipline capable of contributing substantively *independent* theories with *independent* ontological assertions. For this purpose, only physics is a candidate; chemistry, we infer, may at most play the role of mediator in a reduction to physics.

Regarding 3: In what sense is a physical or chemical explanation of relevant functions of life supposed to be *impossible*? This question presents itself in light of the fact that there are more or less radical variants of the conception of this sort of impossibility (not to mention fluid transitions between the individual variants). On the one hand, a reduction might prove *only incompletely* possible, either because a complete reduction would require further principles, or because it can only be approximated on the basis of principles currently in use.[10] On the other hand, such a reduction might prove *completely* impossible, say because the theories mustered in this attempt fail to have any consequences with regard to the phenomena to be reduced, or because their consequences are in irreconcilable contradiction with the phenomena.

Bohr has in mind the *in principle impossibility* of explaining biological phenomena by tracing them back to the physical principles known in his time. This follows from Bohr's own elucidation of the claimed impossibility: "The asserted impossibility of a physical or chemical explanation of the functions peculiar to life would in this sense be analogous to the insufficiency of the mechanical analysis for the understanding of the stability of atoms". (Bohr, 1933, 458). I shall consider this analogy in greater detail later. What's important for present purposes is that, for Bohr, mechanics, which in this context encompasses all of classical physics, including electrodynamics, is insufficient *in principle* for explaining the stability of atoms.[11] Nor may this insufficiency be remedied by *supplementing* mechanics with the additional principles it needs to perform the required explanatory labor. Some of its supposedly universal assertions must rather be *suspended* in order to arrive at an explanation of the stability of atoms; "a radical departure from classical principles [was] inevitable" (Bohr, 1932, 357).[12] This conviction was already of great importance to Bohr in his construction of the atomic model of 1913.[13] We conclude that Bohr wished to assert that reducing biology to physics is impossible in the sense that physics is incapable in principle of explaining the typical phenomena of life. The above analogy suggests a diagnosis of this inability: The characteristic phenomena of life are inexplicable by means of the known physics of 1932, because this physics contains assertions which, in the degree of universality previously attributed to them, are untenable.

2.2. *The Relation of Bohr's Claim to Other Forms of Anti-Reductionism*

In the discussions of reductionism in which, in recent years, philosophers of science and biologists have participated, the distinction between epistemological, ontological, and methodological reductionism has acquired a certain importance. First introduced, to the best of my knowledge, by Ayala (1974), viii – xi, and in greater detail in Ayala (1989), this distinction has subsequently been used in ways both terminologically and substantively divergent. A brief explanation of my use of these three terms is thus in order (compare Hoyningen-Huene, 1985).

Epistemological reductionism is a position characterized by two claims. First, it asserts that all typical biological concepts may, in principle, be given extensionally equivalent redefinitions in terms of physical concepts. Second, all biological laws may be derived from physical laws, with the help of the aforementioned redefinitions and appropriate boundary conditions. *Ontological reductionism* asserts that underlying the processes of life are the very same elemental substrate and interactions that underlie the processes of inanimate nature. *Methodological reductionism* asserts that biological research ought to be conducted on the molecular level alone.

A number of difficulties arise when we attempt to explicate more precisely just what typifies these positions (See Hoyningen-Huene, 1989, and the relevant literature cited there.) For our purposes, however, the brief formulations given above will suffice. How, then, may Bohr's position be characterized in terms of (1) epistemological, (2) ontological, and (3) methodological anti-reductionism?

Regarding 1: Bohr's position implies *epistemological anti-reductionism* with regard to the relationship between biology and physics. This is a consequence of Bohr's assertion that typical biological phenomena can't be traced back to physical concepts and laws (at least not those of 1932); it follows that such concepts and laws (taken together with appropriate boundary conditions) are, in principle, insufficient for the deductive derivation of typically biological laws. We ought to note that this implication of anti-reductionism does not immediately follow from just any assertion of *inexplicability*; it is rather a consequence of employing a particular notion of explanation (compare section 2.1).

Regarding 2: With respect to ontological anti-reductionism, Bohr's position is unmistakable. For he claims that, with regard to the widespread doubt among biologists (of his time) that living phenomena may really be understood on a purely physical basis,

> ... this view, often known as vitalism, scarcely finds its proper expression in the old supposition that a peculiar vital force, quite unknown to physics, governs all organic life. I think we all agree with Newton that the real basis of science is the conviction that Nature under the same conditions will always exhibit the same regularities. Therefore, if we were able to push the analysis of the mechanism of living organisms as far as that of atomic phenomena, we should scarcely expect to find any features differing from the properties of inorganic matter. (Bohr, 1933, 457–458)

Bohr thus subscribes to *ontological reductionism* (compare also Bohr, *APHK*, 21). In light of this fact, the argument Bohr gives in favor of his implicit *epistemological anti-reductionism* becomes especially interesting (Compare Hoyningen-Huene, 1985, 273; and 1989, especially 30–31; also compare Folse 1990a, 215 and 219).

Regarding 3: It should be clear that Bohr's position entails methodological anti-reductionism. If physics is insufficient for the explanation of typical biological phenomena, such phenomena must also be studied at a level higher than the molecular level.

3. THE ARGUMENT FOR THE ANTI-REDUCTIONIST CLAIM

As we have seen, Bohr must argue why physics (or at least the physics of 1932) is insufficient in principle for the explanation of peculiarly biological phenomena. In 3.1, I begin by characterizing Bohr's argument informally. Sections 3.2 and 3.3 examine the two premises of Bohr's argument. Finally, section 3.4 attempts a formally adequate reconstruction of the argument. In *these* sections, my goal is not to criticize the argument. For now, I seek only to identify and explicate the argument's components so as to make it plausible. In section 4, a critique of the argument on the basis of this reconstruction follows.

3.1. *Bohr's Argument: An Analogical Inference*

Bohr's argument for the inexplicability of peculiarly biological phenomena by physics is an analogical inference: "The asserted impossibility of a physical or chemical explanation of the functions peculiar to life would . . . be analogous to the insufficiency of the mechanical analysis for the understanding of the stability of atoms" (Bohr, 1933, 458). According to Bohr, this analogy is supported by the fact that the two domains it connects both coincide in one aspect, which serves as a *tertium comparationis*. Bohr calls this aspect "the essence of the analogy;"

> . . . the essence of the analogy considered is the *typical relation of complementarity* existing between the subdivision required by a physical analysis and such characteristic biological phenomena as the self-preservation and the propagation of individuals. (*Ibid.*, 458, emphasis mine; compare Bohr, 1937a, *APHK*, 21)

Our provisional formulation of Bohr's argument in "Light and Life" is as follows:

Premise 1: An explanation of the stability of atoms by means of (classical) mechanics is impossible given the relation of complementarity which governs such explanation.

Premise 2: The explanation of characteristic biological functions by physics is governed by the same relation of complementarity.

Conclusion: The explanation of characteristic biological functions by physics is thus impossible.

Before I subject the premises and conclusion of this argument to more careful analysis, it must be noted that Bohr restricts the analogy, claiming it holds "only in [one] formal respect";

> ... I wish to stress at once that it is *only in this formal respect* that light, which is perhaps the least complex of all physical phenomena, exhibits an analogy to life, the diversity of which is far beyond the grasp of scientific analysis. (Bohr, 1933, 421, emphasis mine)

In Bohr's usage, "formal" is the complement of "substantive"; his claim that the analogy holds in only "this formal respect" thus implies that there is some substantive disanalogy. As the above passage suggests, the disanalogy lies in the simplicity of light as compared with the "diversity" of life, so great as to exceed the grasp of scientific analysis. But with regard to the present argument, which makes use only of the complementarity obtaining in *both* cases, this substantive restriction on the analogy is without consequence.

Let us now examine the premises of Bohr's argument in greater detail.

3.2. *First Premise: Complementarity in Physics*

The pivotal notion in Bohr's argument is that of complementarity, to which we must now turn. In the discussion which follows, I shall, as far as possible, limit myself to the explanations of complementarity provided in 'Light and Life', since both earlier and later work by Bohr indicates modifications in his conception.

a) *The complementarity of wave and corpuscular natures in light*

In 'Light and Life' Bohr first introduces the notion of complementarity in a context different from that required by premise 1, which concerns, roughly speaking, the relationship between mechanics and quantum mechanics. Instead he employs it in summarizing recent debate on the nature of light. Sketching the successes of Maxwellian electrodynamics, he insists that the conception

> ... of the wave nature of the propagation of light ... can no longer be considered as a hypothesis in the usual sense of this word, but may rather be regarded as an indispensable element in the description of the phenomena observed. (Bohr, 1933, 421)

But immediately afterward, Bohr reminds us that

> ... the problem of the nature of light has, nevertheless, been subjected to renewed discussion in recent years, as a result of the discovery of a peculiar atomistic feature in the energy transmission which is quite unintelligible from the point of view of the electromagnetic theory. It has turned out, in fact, that all effects of light may be traced down to individual processes, in each of which a so-called light quantum is exchanged ... (*Ibid.*, 421)

Bohr has now set the stage for the introduction of a notion of complementarity, for the "atomistic feature" of light is also indispensable in our descriptions of light:

> The spatial continuity of light propagation, on one hand, and the atomicity of the light effects, on the other hand, must, therefore, be considered as complementary aspects of one reality, in the sense that each expresses an important feature of the phenomena of light, which, although irreconcilable from a mechanical point of view, can never be in direct contradiction, since a closer analysis of one or the other feature in mechanical terms would demand mutually exclusive experimental arrangements (*Ibid.*, 422)

This rather complex sentence contains the essential features of the notion of complementarity. Let us consider them separately.

1. The complementarity relation holds between different "aspects of one reality", where "each expresses an important feature of the phenomena". The "importance" of such features lies in fact that they are *indispensable* in any adequate description. As Bohr emphasizes in addressing the wave nature of light, this feature is not "a hypothesis in the usual sense of the word"; it cannot simply be given up or replaced. The wave conception is instead "an indispensable element in the description of the phenomena observed" (*Ibid.*, 421).

2. From a certain "point of view" these different "aspects of one reality" are "irreconcilable".[14] Let us consider the asserted irreconcilability (2a) and the point of view constitutive of it (2b) in turn.

2a) Of precisely what sort is the irreconcilability in question? Lest we be too quick to jump to conclusions, let us examine such explanations as may be found in Bohr's text. Bohr characterizes the relationship between wave and corpuscular conceptions of light by claiming, for example, that the "atomistic feature" of energy-matter interactions "is *quite unintelligible* from the point of view of the electromagnetic theory" (Bohr, 1933, 421, emphasis mine). Similarly, Bohr characterizes the relationship between another pair of complementary poles (which I will discuss in detail later) as follows:

> On this view, the existence of life must be considered as *an elementary fact that cannot be explained*, but must be taken as a starting point in biology, in a similar way as the quantum of action, which appears *as an irrational element* from the point of view of classical mechanical physics, taken together with the existence of the elementary particles, forms the foundation of atomic physics. (*Ibid.*, 458, emphasis mine)

It is tempting to take this irreconcilability or inexplicability as a matter of *logical* contradiction between two complementary poles (or as an immediate conceptual contradiction which, by substitution, may be reformulated as a logical contradiction).[15] But it is clear that the sort of irreconcilability Bohr has in mind *cannot* be reconstructed as the logical or conceptual contradiction between two equally firm givens (such as theories, laws, facts, etc.). An elementary example will suffice to convince us on this score.

Galileo's law of acceleration under free fall and Newton's universal law of gravitation are, when supplemented with appropriate boundary conditions, in direct logical contradiction.[16] The contradiction is easily noticed when we recall that Galileo's law assumes that a body in free fall is subject to a *constant* force, while the universal law of gravitation entails a *variable* force, one which increases with the distance fallen. But of course one would hardly claim that, from the point of view of the universal law of gravitation, Galileo's law is, to use Bohr's words, "quite unintelligible". On the contrary, the relation between the two laws is a standard example of the way a more universal law may *explain* a special law, or as it is sometimes put, how one law may be a *special case* of another. The logical contradiction between two theories (or laws, or hypotheses) by no means rules out the explanation of one by the other, in this case, the approximate derivation of one from the other. Bohr's elucidation of the notion of irreconcilability he has in view thus rules out its being explained, at least immediately, in terms of the notion of logical or conceptual contradiction.

But if Bohr's irreconcilability isn't a matter of logical or conceptual irreconcilability, what is it? In its abstract formulation, what Bohr means must necessarily be rather vague. To say that some theoretical notion B is "quite unintelligible" or "irrational" from the point of view of another theoretical notion (*i.e.* theory, hypothesis, law, etc.) A, is to assert the following: *Even taking into account* all the appropriate approximations, boundary conditions, models, plausible auxiliary assumptions consistent with A, plausible corrections of B, plausible background assumptions, or other bits of scientific knowledge consonant with A which might be adduced, B cannot be made theoretically compatible with A. The contradiction thus is *not* an opposition between two well-defined entities, say A and B themselves. A may rather be supplemented by the potentially open set of additional premises which might, roughly, be called "judicious expansions of A". B may even be corrected, albeit not, normally, in any drastic way, though the corrected B may, of course, be in logical contradiction with the original B. I shall call the irreconcilability in question '*theoretical irreconcilability*'. This notion is of extraordinary importance in physics and the other sciences.

2b) Theoretical irreconcilability, thus described, is not an absolute relation between complementary poles; it is rather relative to the point of view provided by a particular theory (such as the "mechanical point of view" (Bohr, 1933, 422) or the "point of view of the electromagnetic theory" (*Ibid.*, 421). Why and how do such theories provide points of view on which certain aspects of the available phenomena become irreconcilable? The decisive aspect of the classical theories under consideration is that they make ontological assertions about "phenomena as existing independently of the means by which they are observed" (*Ibid.*, 423).[17] Under this assumption, the corpuscular and wave natures of light are indeed irreconcilable: light either *consists* of waves or it *consists* of particles, regardless of anything the observer does. From the point of view of classical physics, the various aspects of the phenomena simply *cannot* be understood as aspects of one and the same thing. The notion of complementarity, according to Bohr, is meant to target the constraints placed on the validity of the aforementioned ontological assertions:

> ... the notion of complementarity serve[s] to symbolise the fundamental limitation, met with in atomic physics, of our ingrained idea of phenomena as existing independently of the means by which they are observed. (Bohr, 1933, 423)

3. But despite their irreconcilability from one point of view, the two complementary sides of a phenomenon "can never be in direct contradiction". "Direct contradiction" refers to logical or conceptual contradiction, such as might occur in the description of certain factual situations. It is conceivable, for example, that in *one* experimental situation light might be described *both* as a wave *and* as a corpuscle, or perhaps even had to be described in both ways, resulting in a logical or conceptual contradiction. Nor could this contradiction be resolved, for Bohr, by recourse to the claim that the contradiction rests on the typical presuppositions of classical physics, presuppositions abandoned by quantum physics. Such recourse isn't open to Bohr, because from 1927 on (at the latest), he believes that quantum theory cannot simply do without the classical concepts (including the necessary conditions for their meaningful application).[18] And so we find him claiming, at the beginning of §1 of his Como lecture, immediately following the introduction,

> The quantum theory is characterised by the acknowledgement of a fundamental limitation in the classical physical ideas when applied to atomic phenomena. The situation thus created is *of a peculiar nature, since our interpretation of the experimental results rests essentially upon the classical concepts*. (Bohr, 1928, 580, emphasis mine)[19]

So if, quantum physics notwithstanding, we are to continue employing the concepts of classical physics, there must be some other way of avoiding the imminent contradictions. According to Bohr, a "closer analysis" (Bohr, 1933, 422) reveals the *physical prevention of contradictions*: the two classes of experimental situations in which light manifests wave-features and corpuscular features, respectively, are physically exclusive of one another. Bohr explains this view a little further in "Light and Life", just prior to his introduction of the notion of complementarity:

> ... it is characteristic of all the phenomena of light in which the wave picture plays an essential role, that any attempt to trace the paths of the individual light quanta would disturb the very phenomenon under investigation; just as an interference pattern would completely disappear if, in order to make sure that the light energy travelled only along one of the two paths between the source and the screen, we should introduce a non-transparent body into one of the paths. (Bohr, 1933, 422)

Experimental conditions conducive to studying the paths of individual light corpuscles would thus destroy just those phenomena whose description depends essentially on the wave picture.

Insofar as it bears on the dualism of wave and corpuscular notions of light, Bohr's notion of complementarity has been sufficiently clarified. What remains entirely unclear, however, is the bearing this notion has on the impossibility of explaining the stability of atoms by means of classical physics. If we want to understand what allows Bohr's first premise to play the role it does in his argument, this connection must be explained.

b) *Complementarity of mechanics and quantum mechanics*

The second appearance of the notion of complementarity in 'Light and Life' is in the context of Bohr's presentation of the "remarkable development of the atomic theory" in "recent years" (Bohr, 1933, 422) with the emergence of matrix mechanics, and its equivalent, wave mechanics. According to Bohr, there is a close relationship between this development and the problems of light:

> Although the rational treatment of the problems of atomic mechanics was possible only after the introduction of new symbolic artifices, the lesson taught us by the analysis of the phenomena of light is still of decisive importance for our estimation of this development. (Bohr, 1933, 422)

In the English version which appears in *APHK*, the corresponding sentence is clearer and more concise: "Notwithstanding the greater complexity of the general problems of of atomic mechanics, the lesson taught us by the analysis of the simpler light effects has been most important for this development" (*APHK*, 6). But in what respect did what was learned in the analysis of light prove so important in the development of quantum mechanics? In the following sentence, Bohr explains,

> ... an unambiguous use of the concept of a stationary state is complementary to a mechanical analysis of intra-atomic motions; in a similar way the idea of light quanta is complementary to the electromagnetic theory of radiation. (Bohr, 1933, 422; similarly *APHK*, 6)

Thus the more *general* lesson, gleaned from the analysis of the phenomena of light and applied in the further development of quantum mechanics, resides in the notion of complementarity, which proved more broadly applicable outside the domain of light phenomena.

In consequence, three aspects of the notion of complementarity relevant to the dualism of wave and corpuscular pictures of light may be applied to the relationship between the "unambiguous use of the concept of a stationary state" and "a mechanical analysis of intra-atomic motions". In turn, the new complementarity claim which, since the notion of complementarity was introduced earlier, requires justification, entails three further claims, each of which is also in need of justification.

First claim: Both the concept of a stationary state and the mechanical analysis of intra-atomic motion capture different, but equally indispensable aspects of one and the same thing.

Justification: Bohr's text doesn't offer any explicit justification. It is obvious that the notion of a stationary state does, indeed, capture a fundamental trait of atoms. But it is far less clear which essential features of atoms may be captured by the mechanical, i.e. *classical* analysis of intra-atomic motion, but aren't subject to quantum-mechanical analysis (just as the wave features of light aren't subject to analysis based on the corpuscular account, and vice versa). In this respect, the two situations aren't entirely congruent.

Second claim: From a certain point of view, the unambiguous employment of the concept of a stationary state and the mechanical analysis of intra-atomic motion are theoretically irreconcilable.

Justification: Once again, Bohr's text offers no explicit justification, though such may be given, up to a point, with relative ease. For the concept of a stationary state to be employed unambiguously in fact requires that all atomic states (or energy states) be stationary (compare *e.g.* Bohr, 1925, 847). Consequently, no trajectory may be ascribed to an electron in transition from one stationary state to another, for otherwise the atom would have to have states of different energy than that of any of its stationary states. So far, the justification of the second claim appears cogent.

But what is the "point of view" from which this theoretical irreconcilability emerges? By analogy to wave-particle dualism, this point of view may be given a preliminary, negative characterization: The point of view in question is one which fails to take account of the relativization of both unambiguous employment of the concept of a stationary state and mechanical analysis of intra-atomic motion to mutually exclusive experimental situations (see also the third claim). In positive terms, this failure implies the acceptance of an ontological assumption, which in turn gives rise to the theoretical irreconcilability. The assumption in question is that, in general, i.e. regardless of experimental conditions, a particle is *either* spatio-temporally localized (and thus accessible to mechanical analysis), or it isn't (and hence may only be described by reference to the notion of a stationary state). But this assumption implies a forced and *final* choice between the concepts with which classical mechanics describes particles on the one hand, and those of quantum mechanics on the other, a choice which, for Bohr, is unacceptable (see section 3.2.a), point 3).

Third claim: There is no physical way for the unambiguous employment of the concept of a stationary state and the mechanical analysis of intra-atomic motion to come into direct contradiction. This claim breaks down into two sub-claims. 3a) Any experimental arrangement which sanctions the unambiguous employment of the concept of a stationary state physically rules out the mechanical analysis of intra-atomic motion. 3b) Any experimental arrangement which sanctions a mechanical analysis of intra-atomic motion physically rules out the unambiguous employment of the concept of a stationary state.

Justification: Only for this third assertion, in which, after all, the novelty of his notion of complementarity resides, does Bohr offer any explicit justification in the passage immediately following the new complementarity claim:

> ...any attempt to trace the detailed course of the transition process would involve an uncontrollable exchange of energy between the atom and the measuring instruments, which would completely disturb the very energy transfer we set out to investigate. (Bohr, 1933, 422)

Bohr has provided an example for sub-claim 3a) as it applies to transition processes: The occurrence of any *given* transition is physically incompatible with the simultaneous examination (say by means of photons) of the electron motion involved, since such examination would produce an uncontrollable effect on the electron, thus disturbing the very process under study (compare Bohr, 1928, 587, 589).

Bohr's justification for sub-claim 3b, however, is far less clear. Following the sentence cited above, Bohr asserts, "A causal description in the classical sense is possible only in such cases where the action involved is large compared with the quantum of action..." (Bohr, 1933, 422).

If this is right, then by 3b, the unambiguous employment of the concept of a stationary state would be physically ruled out for cases in which the relevant actions are large compared with the quantum of action. In his Como lecture, however, we find Bohr claiming that "in the limit of large quantum numbers where the relative difference between adjacent stationary states vanishes asymptotically", i.e. in one situation involving large actions,

> ...mechanical pictures of electronic motion can be rationally utilised. It must be emphasized, however, that this...cannot be regarded as a gradual transition towards classical theory in the sense that the quantum postulate would lose its significance for high quantum numbers. On the contrary, the conclusions obtained from the correspondence principle with the aid of classical pictures depend just upon the assumptions that the *conception of stationary states* and of individual transition processes are maintained *even in this limit*. (Bohr, 1928, 589, emphasis mine)

Here, too, it appears that a different complementarity relation obtains than that governing the dualism of wave and corpuscular conceptions. While the latter case exhibits full symmetry between wave and corpuscular conceptions, the asserted complementarity between the unambiguous employment of the concept of a stationary state and the mechanical analysis of intra-atomic motion manifests certain asymmetries.

Still, at least as far as the argument under consideration is concerned, these differences strike me as irrelevant.[20] For Bohr's notion of complementarity is meant to address the mechanism whereby contradiction between two theoretically irreconcilable, but equally indispensable counterparts is avoided. Here the counterparts are mechanics and quantum mechanics, which though theoretically irreconcilable are both needed in physics. And here, once again, we find that the threat of inconsistency is physically barred, for peculiarly quantum-mechanical effects can't be studied with classical means without destroying the very quantum phenomena in question.

Has Bohr's first premise been justified? It has, at least insofar as the complementarity diagnosis is correct. We recall that it was the effort to account for irreconcilability which necessitated the recourse to the physical prevention of contradictions, the whole point of the notion of complementarity. If classical mechanics and the employment of the concept of a stationary state are indeed complementary, it follows that they are theoretically irreconcilable. Thus the characteristic stability of atoms can't, in principle, be explained by mechanics.

3.3. *Second Premise: Complementarity of Physics and Biology*

According to Bohr, the relationship between the entirety of physics (classical physics together with quantum mechanics) and biology is governed by complementarity analogous to that which holds between classical mechanics and typical quantum-mechanical phenomena. The "essence" of the analogy, for Bohr "... is the typical relation of complementarity existing between the subdivision required by a physical analysis and such characteristic biological phenomena as the self-preservation and the propagation of individuals". (Bohr, 1933, 458; compare *APHK*, 21). This claim, like the extension of the notion of complementarity from wave-corpuscle duality to the relationship between mechanics and quantum mechanics discussed in the last section, breaks down into three sub-claims, each of which requires its own justification.

First claim: Both the results of physical analysis on the one hand, and descriptions which employ such concepts as "self-preservation" and "propagation of individuals" on the other, capture essential aspects of living organisms.

Justification: Bohr emphasizes that both classical physics and quantum mechanics are needed in order to explain many features of organisms. For example, quantum mechanics is indispensable to our understanding of "the carbon assimilation of plants" or "the characteristic properties of such highly complicated chemical compounds as chlorophyll or haemoglobin" (457). Bohr summarizes his view of the role of physics in biology as follows:

> An understanding of the essential characteristics of living beings must be sought, no doubt, in their peculiar organization, in which features that may be analysed by the usual mechanics are interwoven with typically atomistic traits in a manner having no counterpart in inorganic matter. (457; also compare Bohr 1937a, *APHK*, 20)[21]

In order to avoid misunderstandings, it is worth emphasizing that this passage in no way asserts that classical physics and quantum mechanics are *sufficient* for an "understanding of the essential characteristics of living beings", though Bohr certainly claims that they are *necessary*. Such typical biological concepts as those of self-preservation and propagation are equally necessary in the description of organisms; the phenomena they describe, for Bohr, are just the "characteristic biological phenomena" (Bohr, 1933, 458).

Second claim: From a certain point of view, the results of a physical analysis of living beings and their description by means of characteristic biological concepts are theoretically irreconcilable.

Justification: The theoretical irreconcilability of physical and biological descriptions of living beings appears to be self-evident to Bohr in the context of his application of the notion of complementarity to biology; at any rate, he offers no justification. And so we find him talking of "...the wonderful features which are constantly revealed in physiological investigations and *differ so strikingly* from what is known of inorganic matter..." (Bohr, 1933, 457, emphasis mine). Or similarly, Bohr claims "...the concept of purpose, *which is foreign to mechanical analysis*, finds a certain field of application in problems where regard must be taken of the nature of life". (*Ibid.* 458, emphasis mine). A clarification of the special point of view from which the theoretical irreconcilability of physics and biology arises will have to wait until we have considered the third sub-claim.

Third claim: The results of a physical analysis of living beings and their description by means of characteristically biological concepts may never, on physical grounds, come into direct contradiction.

Justification: Only for this claim may we find any detailed justification in the immediate neighborhood of the complementarity claim of "Light and Life". Bohr begins by drawing attention, on the one hand, to the fact that certain results of physiological investigations are scientifically irreconcilable with physics, and on the other, to the need to reject ontological anti-reductionism, or the vitalist view which postulates "a peculiar vital force, quite unknown to physics" (*Ibid.*, 457–458; compare section 2.2 above). But the rejection of vitalism has the following further consequence: "...if we were able to push the analysis of the mechanism of living organisms as far as that of atomic phenomena, we should scarcely expect to find any features differing from the properties of inorganic matter" (*Ibid.*, 458). Now a "dilemma" arises (*Ibid.*, 458): If the components of both animate and inanimate matter follow the *same* laws, it's not immediately clear why they should be different with respect to their explanation by physics. Bohr presents the solution to this dilemma or apparent contradiction as follows:

> With this dilemma before us, we must keep in mind, however, that the conditions holding for biological and physical researches are not directly comparable, since the necessity of keeping the object of investigation alive imposes a restriction on the former, which finds no counterpart in the latter. Thus, we should doubtless kill an animal if we tried to carry the investigation of its organs so far that we could describe the role played by single atoms in vital functions. (*Ibid.*, 458; compare Bohr, 1937a, in *APHK*, 20–21)

In other words, the conditions under which an organism becomes an appropriate object for (atomic) physics are incompatible with the organism's continued life[22]. Therefore, the conditions under which an organism is an appropriate object for biological study, *i.e.* those under which it gives rise to the characteristic phenomena of life, make the employment of physical concepts impossible.

Where, then, ought we to seek the "point of view" to which the theoretical irreconcilability of physics and biology is proper? Once again, the analogous complementarity of the wave-corpuscle dualism sanctions a preliminary, negative characterization: The point of view in question is one which fails to take account of the relativization of the applicability of both physical and biological concepts to mutually exclusive experimental situations. In positive terms, this failure implies the acceptance of an ontological assumption which gives rise to theoretical irreconcilability. The assumption is that organisms in general, *i.e.* independently of experimental conditions, are *either* machines in the sense of being wholly accessible to physical analysis, *or* structures obedient to laws fundamentally different from those of physics. This assumption implies a forced and *final* choice between mechanism and vitalism, a choice Bohr would find unacceptable.

Has Bohr's second premise been justified? Insofar as the complementarity diagnosis is correct, it has, for if physics and the functions peculiar to life are indeed complementary, they must be theoretically irreconcilable. It follows that the functions peculiar to life can't, in principle, be explained by physics.

3.4. *Formal Reconstruction of Bohr's Argument*

Having analyzed both of its premises, we must now consider Bohr's argument as a whole. As presented in section 3.1, the argument is formally invalid, for the requisite universal premise is missing (compare Lorenz, 1980). Here is a formally valid rendition of the inference:

Premise 1: Whenever A and B are complementary, it is impossible to explain B by A.

Premise 2: Physics and characteristic biological functions are complementary.

Conclusion: The explanation of characteristic biological functions by physics is thus impossible.

Notice that the conclusion of the inference is the same as on our earlier rendition. Reconstructing the inference in this way requires that we view Bohr's discussion of the wave-corpuscle dualism as serving to *introduce* the notion of complementarity, while his treatment of the complementarity of mechanics and quantum mechanics *illustrates* the new first premise. It now appears that Bohr's argument is an attempt not only to prove the irreducibility of biology to physics, but also to show that both disciplines, despite their theoretical irreconcilability, have a place in the edifice of science.

4. CRITIQUE OF BOHR'S ANTI-REDUCTIONIST ARGUMENT

Our critique of Bohr's argument, as formulated in section 3.4, will have to focus on its second premise, for the first premise follows analytically from the conception of complementarity itself.[23] What constitutes appropriate grounds, in a given situation, for a correct diagnosis of complementarity? It must be shown that all three features of complementarity really apply to the situation in question. In other words: (1) Two indispensable aspects of the phenomenon at issue must be identified; (2) These two aspects must, from some point of view (one previously held to be valid), be theoretically irreconcilable; and (3) The two aspects may never actually be in contradiction, because each occurs only under experimental conditions which physically exclude the other. In 'Light and Life' Bohr's assertion that physics and characteristic biological functions are complementary rests on the applicability of the first and third features of complementarity; he never argues that the second feature applies (compare section 3.3). Now, the claim that the proprietary experimental methods of physics are incompatible with the persistence of peculiarly biological phenomena – Bohr's application of the third feature of complementarity – may be challenged, and on good grounds. Later, Bohr himself seems to have accepted the challenge.[24] But the real weakness of Bohr's argument lies elsewhere.

This weakness becomes apparent when we consider how the application of the second feature of complementarity to a given situation would have to be justified. It would have to be shown that, from the previously accepted perspective, two aspects of the relevant phenomenon are mutually incompatible. In particular, it would have to be shown that neither of the two aspects can be expressed in terms of the other. But this just means that neither of the two aspects is reducible to the other, in the epistemic sense. The mutual epistemological irreducibility of the two aspects is thus a *necessary condition* for their complementarity. So it is impossible to prove irreducibility by *means* of complementarity, on pain of circularity.[25]

Any demonstration of the existence of a mechanism which prevents two aspects of the same phenomenon from manifesting themselves in one and the same situation, taken by itself, is theoretically uninteresting. Even if it were the case that the methods of measurement proper to physics are fundamentally incompatible with the existence of life, nothing would follow with regard to the reducibility or irreducibility of biology to physics. Analogously, if it were impossible, on physical grounds, to measure both the electrical conductivity and optical reflectivity of a given body in one and the same situation, nothing would follow with respect to the theoretical relationship between the two parameters. The mutual, physical exclusion of two aspects of a phenomenon is of interest only when their theoretical irreconcilability has already been established.

It seems to me that in 'Light and Life' Bohr is pursuing two distinct, albeit related goals. On the one hand, Bohr presupposes the theoretical irreconcilability of biology and physics, attributing the same presupposition to biologists in general (Bohr, 1933, 421, 457). If, however, we deny the fruitfulness of vitalism, we must ask how it is that the mutually irreconcilable disciplines of physics and biology both have a place in the edifice of science. One answer to this question is to assert the mutual, physical exclusion of the two classes of phenomena, hence their complementarity.

On the other hand, Bohr is also interested in actually *arguing* the theoretical irreconcilability of biology and physics. As was noted in the introduction, as late as 1931 Bohr takes the issue of biology's reducibility or irreducibility to be "a quite open question". At the very outset of his discussion of the present status of biology, Bohr explicitly states that "... [t]he *question* at issue ... is whether some fundamental traits are still missing in the analysis of natural phenomena, before we can reach an understanding of life on the basis of physical experience" (Bohr, 1933, 457, emphasis mine). This question is treated in such a way as to allow Bohr, finally, to talk of the "asserted impossibility of a physical or chemical explanation of the functions peculiar to life" (*Ibid.*, 458). This assertion may not, however, be justified by an argument *which invokes complementarity.*[26]

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NOTES

[1] Meyer-Abich comes to the same conclusion in (1965), 181.

[2] See the "Preface" to *ATDN* on the dates of composition for the "Introductory Survey" and its "Addendum".

[3] For a detailed presentation of the institutional circumstances of Delbrück's career, see Kay (1985b).

[4] For an account of the circumstances of this discovery from Watson's perspective, see his well-known book *The Double Helix*, Watson (1968). See the contributions to Stent (1980) for commentaries on this book. For further literature, see *e.g.* Winkler (1985).

[5] Footnote to English and German versions.

[6] In the discussion which follows, I shall treat Bohr's (1937a) and (1957), which deal with the same issues as "Light and Life", only in passing, since they do not substantively go beyond "Light and Life;" *q.v. APHK*, 74–76; and 91–92, and *Essays*, 20–21. For Pascual Jordan's reception of Bohr's argument, see Jordan (1932) and (1934), and for the discussion this precipitated in the Vienna Circle, see Bünning (1935), Frank (1935), Neurath (1935), Reichenbach (1935), Schlick (1935), and Zilsel (1935). See Heitler (1976) for a contemporary attempt at a revival of Bohr's argument. Hoyningen-Huene (1991a), (1991b), and (1992) contain earlier, substantially shorter analyses of Bohr's argument. The focus of these papers is on a "theory of anti-reductionist arguments", and on the role Bohr's argument might play in such a theory.

[7] In his (1929), Bohr cites "the freedom and power of adaptation of the organism in its reaction to external stimuli" as examples of "more profound biological problems" (*ATDN*, 118). In that portion of the "Introductory Survey" composed in 1929, Bohr claims that "living individuals are first of all characterized by the sharp separation of the individuals from the outside world and their great ability to react to external stimuli" (*ATDN*, 20–21). While I do not know what moved Bohr to change his choice of examples for what is characteristic of life, this issue is of only subordinate importance here.

[8] A similar claim is made in Bohr (1937a), where he states that quantum mechanics has offered "a complete explanation of the remarkable relationships between the physical and chemical properties of the elements, as expressed in the famous periodic table of Mendeleev" (Bohr, (1937a), *APHK*, 18).

[9] Similar passages with the same tone may be found in Bohr (1932), on 359, 363, 366, 368, and 373. Folse even claims that, for Bohr, the reduction of chemistry to physics is the whole purpose of atomic physics; "Bohr understood the fundamental task of atomic physics to be accounting for the properties of the chemical elements in terms of atomic structures" (Folse, 1985, 57). Also compare Kragh (1985a) (especially 50–51) and Kragh (1985b). – That the conviction, as widespread among physicists today as it was then, that chemistry must, at least in principle, be reducible without remainder to physics, is not only *not* self-evidently true, but perhaps even false, has recently been noted, especially by Hans Primas. See Primas (1981), (1985a), and (1985b).

[10] In his (1974), Popper argues that many apparently successful reductions in the history of science are incomplete in this sense.

[11] Many passages in Bohr's work support this reading. See e.g. Bohr (1925), 847; (1932), 355, 356, 357, 377.

[12] Two assumptions or consequences of Bohr's 1913 atomic model, in particular, are incompatible with classical physics. The first is the existence of so-called stationary states, in which a charge, despite undergoing what, in mechanical terms, is accelerated motion, doesn't radiate. The second, "perhaps the greatest and most original of Bohr's breaks with existing tradition" (Heilbron and Kuhn, 1969, 266), though less well-known than the first, consists in Bohr's separation of the mechanical oscillation frequencies of charges from the frequencies of electromagnetic radiation.

[13] See *e.g.* Folse (1985), 61–64, 184; and Rosenfeld (1967), 118. See Heilbron and Kuhn (1969) and Hoyer (1974) for the historical details.

[14] That such contradiction is a central, hence indispensible element of complementarity has been emphasized, most notably, by Drieschner (1979), 152; *q.v.* Röseberg (1984), especially 237f.
[15] At any rate, this reading has had some appeal to contemporary philosophers of science; see *e.g.* Scheibe (1988), 169–170.
[16] See Feyerabend (1962), 88; and (1976), Ch. 3. See also Krajewski (1984), 11–12, and Hoyningen-Huene (1985), 275–276.
[17] Compare section 2.1, point 2.
[18] It seems to me that Bohr only arrived at the view that, despite quantum physics, classical concepts are indispensible, *after* 1925; His 1925 essay "Atomic Theory and Mechanics" still argues for the *complete abandonment* of classical concepts and spatio-temporal notions. Unfortunately, limited space prevents me from presenting in detail the textual evidence for this view, which diverges, for example, from that of Folse (1985), 99–101 and Murdoch (1987), 31–33.
[19] See Feyerabend (1958), 81–89, for a critique of this assumption of Bohr's.
[20] For attempts to differentiate the notion of complementarity aimed at separating out distinct notions (only some of which are relevant to physics), see Drieschner (1979), 152; Folse (1985), 269–270; Honner (1987), 58–59; Hyland and Kirsch (1988); MacKay (1958); Murdoch (1987), 58–61; Redhead (1987), 170–171; and von Weizsäcker (1955), 284–297; and (1957).
[21] Bohr had already noted both the possibility and necessity of subjecting certain aspects of biological phenomena to physical explanation in his (1929), *ATDN*, 117–118 and *ATDN*, 21.
[22] In his (1937a), Bohr supplements this argument with the following remark: "The incessant exchange of matter which is inseparably connected with life will even imply the impossibility of regarding an organism as a well-defined system of material particles like the systems considered in any account of the ordinary physical and chemical properties of matter" (Bohr, 1937a, in *APHK*, 20–21).
[23] For a different approach to the critique of Bohr's argument, see Folse (1985), 183–193.
[24] Although Bohr's statements in his (1962), *Essays*, 26, aren't entirely unequivocal. For Stent, the case is closed with the discovery of the structure and function of DNA; "Bohr's conjecture that one needs to kill an organism in order to study it at the atomic level and that this is bound to hide the ultimate secrets of life from us turned out to be wrong" (Stent, 1989, 13).
[25] Theoretically, there are two conceivable ways in which this circularity might be avoided. First, one might attempt to show that the second feature of complementarity is implied by the first. However, this appears not to be the case. One might also attempt to find a criterion of complementarity which doesn't invoke the irreducibility of the aspects involved. No such criterion is currently known, and it is highly doubtful that there even is one.
[26] I am very grateful to Alexander Levine, who translated this essay from the German.

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