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Bringing the human actors back on stage: the personal context of the Einstein–Bohr debate

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INTRODUCTION

In concluding his 'Autobiographical notes', Albert Einstein explained that the purpose of his exposition was to 'show the reader how the efforts of a life hang together and why they have led to expectations of a definite form'.[1] Einstein's remarks tell of a coherence between personal 'strivings and searchings' and scientific activity,[2] which has all but vanished in the midst of the current trend of social constructivism in history of science. As Nancy Nersessian recently pointed out, in the process of illuminating complex relationships between scientific activity and its social context, 'socio-historical analysis has "black-boxed" the individual scientist'.[3] Has the pendulum swung too far? In reaction to the preceding great-man hagiographic approach to the history of science, the social constructivists have largely 'thrown the baby out with the bathwater': consideration of

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[1] A. Einstein, 'Autobiographical notes', in *Albert Einstein: Philosopher-Scientist* (ed. P. A. Schilpp), Evanston, Ill., 1949, 94.

[2] Einstein, op. cit. (1), 3.

[3] N. Nersessian, 'The cognitive sciences and the history of science', in *Conference on Critical Problems and Research Frontiers in History of Science and History of Technology, Madison, Wisconsin*: History of Science Society, 1991, 96. Lorraine Daston and Michael Otte seem to encourage this, writing that 'Individual style may be consigned to the psychoanalytical blackbox of quirk and creativity' (L. Daston and M. Otte, 'Introduction: style in science', *Science In Context* (1991), 4, 230). This black-boxing applies to both the 'micro-sociological' studies of the social interactions within a single laboratory or community, e.g. A. Pickering, *Constructing Quarks*, Edinburgh, 1984; B. Latour and S. Woolgar, *Laboratory Life*, 2nd edn, Princeton, 1986; B. Latour, *Science in Action*, Cambridge, Mass., 1987; and S. Traweek, *Beamtimes and Lifetimes*, Cambridge, Mass., 1988, and the 'macro-sociological' investigations of cultural influences and the problems of social order, e.g. P. Forman, 'Weimar culture, causality, and quantum theory, 1918–1927: adaptation by German physicists and mathematicians to a hostile environment', *Historical Studies in the Physical Sciences* (1971), 3, 1–115; and S. Shapin and S. Schaffer, *Leviathan and the Air-Pump*, Princeton, 1985. Cf. H. Radder, 'Normative reflexions on constructivist approaches to science and technology', *Social Studies of Science* (1992), 22, 141–73 for a recent critique of various socio-historical approaches.

individual scientists' personal approaches to science was unnecessarily expunged with the removal of 'genius' as an explanatory tool.

This gap becomes evident when considering the Einstein–Bohr debate over quantum mechanics. On one side of the pendulum's swing, old-style depictions characterize the debate as a mythic 'battle of the titans', in which Einstein's 'genius' was checked by the strange new world of the quantum of action.[4] Such hagiographic story-telling offers little insight into the roots of the controversy. Yet on the other extreme, newer socio-historical approaches face similar difficulties, because, in a certain sense, both Albert Einstein and Niels Bohr *were* 'titans'. To borrow Martin Rudwick's terminology, Einstein and Bohr were members of the same 'élite core set' of physicists in the 1920s and 1930s.[5] Both Einstein and Bohr had been early 'insider' architects of quantum theory, and they received back-to-back Nobel prizes in 1921 and 1922. By the time quantum mechanics was introduced in 1925–26, the two were both recognized by the physics community as leaders who took charge equally in defining problems and judging solutions. Within the same basic social and intellectual environment, however, Einstein and Bohr immediately fell into dispute over whether or not to accept quantum mechanics. Their thirty-year debate was interrupted only by Einstein's death in 1955, rather than by any mutually agreeable solutions. Thus, the group dynamic models of the social analysts, like the great-man histories they aim to replace, fail to illuminate the roots of the controversy: just as the Einstein–Bohr debate was more than an intellectual argument carried on by two geniuses, so too was it more than merely a play of social interests and influences.

To understand the Einstein–Bohr debate we should, as Martin Rudwick writes, 'bring the human actors on stage'.[6] In other words, we must examine the *personal context* of the Einstein–Bohr debate: why did the two members of a shared scientific community develop different ideas about the goals of science, the qualities of a good scientific explanation, and the criteria for accepting theories? These personal approaches to science were rooted in and shaped according to their individual beliefs, motivations, and patterns of thinking about physical problems. At its foundation, the Einstein–Bohr debate thus reflected a deep-seated difference of *personality*.

This historiographical use of 'personality' relies in a straightforward manner upon its definition: 'The totality of qualities and traits, as of character or behavior, that are peculiar to an individual person... The pattern of collective character, behavioral, temperamental, emotional, and mental traits of an individual'. Evelyn Fox Keller has illustrated this use of 'personality' in historical biography: 'Every scientist comes to his subject with a world view that is uniquely his own – a world view reflected in his relations to people as well as to his subject. Each brings a distinct set of interests – interests stamped by his or her own personality.'[7]

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[4] R. Moore, *Niels Bohr: The Man, His Science, and the World They Changed*, Cambridge, Mass., 1966, 177. Cf. B. Hoffman, *Albert Einstein: Creator and Rebel*, New York, 1972; and J. Bernstein, *Einstein*, New York, 1973.

[5] See M. Rudwick, *The Great Devonian Controversy*, Chicago, 1985, 418–28.

[6] Rudwick, op. cit. (5), 409.

[7] E. F. Keller, *A Feeling for the Organism*, New York, 1983, 49–50. Cf., e.g., M. Klein, *Paul Ehrenfest*, New York, 1970, i; T. L. Hankins, 'In defense of biography: the use of biography in the history of science', *History of Science* (1979), 17, 1–16; J. Heilbron, *The Dilemmas of an Upright Man: Max Planck as Spokesman for*

At best, the literature on the Einstein–Bohr debate has rendered incomplete analyses of this personal context, and has not critically examined how Einstein's and Bohr's distinct lifelong efforts led to conflicting 'expectations of a definite form'. The previous accounts have either failed to heed the socio-historians' sensitivity regarding whiggish analysis, failed to examine the physicists' personal approaches to science, or both. The scientific biographies of Einstein and Bohr, for example, offer some anecdotal clues about Einstein's and Bohr's scientific personalities. Yet the biographies present highly asymmetric accounts of the debate, in which one of the disputants stubbornly rejected the other's 'true', 'correct', or 'justified' position.[8] Philosophers' accounts of the debate similarly stumble into the pitfall of asymmetry, and further remove themselves from the personal context of the debate by distilling off the protagonists' positions as disembodied postulates and schema.[9]

A noteworthy exception is Arthur Fine's *The Shaky Game: Einstein, Realism, and the Quantum Theory*, which examines Einstein's personal approach to the Einstein–Bohr debate. Fine sets sophisticated investigations of Einstein's philosophical position and physical arguments regarding quantum mechanics within a context of personal 'motivations'. He succeeds in dispelling the common myth, as expressed, for instance, by

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German Science, Berkeley, 1986; and C. Smith and M. N. Wise, *Energy and Empire: A Biographical Study of Lord Kelvin*, Cambridge, 1989. This biographical use of 'personality' eschews the psychologist's explanation in terms of 'traumas' and 'neuroses', which, as Lorraine Daston explains, evokes a 'common horror' from historians, sociologists, and philosophers of science alike. (L. Daston, 'The moral economy of science', in *Critical Problems and Research Frontiers*, op. cit. (3), 424.)

[8] On Einstein, see, e.g., P. Frank, *Einstein: His Life and Times*, New York, 1947; Hoffman, op. cit. (4); Bernstein, op. cit. (4); and A. Pais, 'Subtle is the Lord...': The Science and the Life of Albert Einstein, New York, 1982. On Bohr, see, e.g., Moore, op. cit. (4); S. Rozental (ed.), *Niels Bohr: His Life and Work as Seen by his Friends and Colleagues*, New York, 1967; and A. Pais, *Niels Bohr's Times in Physics, Philosophy, and Polity*, Oxford, 1991. Of all these biographies, Pais' pair offers the most valuable insight into both Einstein's and Bohr's personalities and styles of work. Yet his books are limited by Pais' own indifference to history and philosophy of science: he dismisses efforts to trace philosophical roots of Bohr's complementarity as 'without basis in fact', and declares himself 'unable to appreciate what all the fuss is about', regarding the Einstein–Podolsky–Rosen paper (Pais, *Niels Bohr's Times*, 1991, 24, 430). For more on the need for symmetry in historical accounts of controversy, cf. D. Bloor, *Knowledge and Social Imagery*, 2nd edn, Chicago, 1991, 175–9; Shapin and Schaffer, op. cit. (3), 11–12; and Rudwick, op. cit. (5), 12.

[9] Both Henry Folse's and Dugald Murdoch's book-length investigations of Bohr's philosophy of physics dedicate merely fleeting glances to Einstein's position: H. Folse, *The Philosophy of Niels Bohr: The Framework of Complementarity*, New York, 1985; and D. Murdoch, *Niels Bohr's Philosophy of Physics*, New York, 1987. Symmetric accounts address both sides equally, but further dissolve the people behind the arguments: Einstein and Bohr the physicists, with particular motivations, goals and 'expectations', are nowhere to be found. Cf., e.g., C. A. Hooker, 'The nature of quantum mechanical reality: Einstein versus Bohr', in *Paradigms & Paradoxes: The Philosophical Challenge of the Quantum Domain* (ed. R. Colodny), Pittsburgh, 1972, 67–302; and M. Bunge, 'The Einstein–Bohr debate: who was right about what?', in *Einstein Symposium Berlin* (ed. H. Nelkowski), New York, 1979, 204–19. All of these philosophical accounts of the debate share a common disregard for how Einstein's and Bohr's respective positions reflected the physicists' own particular approaches to science.

Henry Folse has recently called for a redrawing of philosophers' maps of the Einstein–Bohr debate, in order better to reflect the issues the way they were actually discussed by the participants (H. Folse, 'Niels Bohr's concept of reality', in *Symposium on the Foundations of Modern Physics* (ed. P. Lahti and P. Mittelstaedt), Singapore, 1987, 161–79; H. Folse, 'The Bohr–Einstein debate and the philosophers' debate over realism versus anti-realism', paper presented at the June 1992 Beijing Conference on Realism). This approach on the philosophers' side fits nicely with the personal-context approach to history of science addressed here. My thanks to Professor Folse for providing copies of these papers.

Werner Heisenberg, that Einstein's opposition to quantum mechanics was due to close-minded dogmatism and old age.[10] Yet Fine merely *displaces* the label of 'dogmatism' from Einstein to Bohr, writing that 'the tale of Einstein grown conservative in his later years is here seen to embody a truth dramatically reversed. For it is Bohr who emerges the conservative, unwilling (or unable?) to contemplate the overthrow of the system of classical concepts...[w]hereas...Einstein's analytical method kept him ever open-minded, always the gadfly who would not be tranquilized.'[11] Fine continues his asymmetric treatment of the debate by writing that instead of 'philosophical depth', Bohr's 'tendency to obscure language' merely reflected 'positivist slogans and dogmas'.[12] Other than this polemic and similar trivializing characterizations, no attention is granted to Bohr's position, and none at all to the personal context behind it. For all the gains in understanding some roots and meanings of Einstein's position, Fine's analysis in the end falls dramatically short of solving the mysteries of the Einstein–Bohr debate.

A critical use of the existing literature provides a framework within which a new investigation may begin. The primary sources, including published and unpublished articles, lectures, interviews, and correspondence, reveal the personal context of the Einstein–Bohr debate. They point toward solutions to the question of how different 'efforts of a life hang together' and lead to 'expectations of a definite form', and help us to understand why Einstein's and Bohr's approaches remained irreconcilable. The Einstein–Bohr debate sprang in fundamental ways from personal scientific considerations. Within essentially the same social context, Einstein and Bohr developed different methodologies and criteria for judging theories. These differences reflected the physicists' contrasting personal temperaments and cognitive orientations, and came to a head over the acceptance or rejection of quantum mechanics. To unravel the debate, therefore, we must begin by examining the core of the conflict: the personalities behind Einstein's and Bohr's respective approaches to science.

PERSONAL TEMPERAMENTS AND COGNITIVE ORIENTATIONS

Language versus imagery

The primary difference separating Niels Bohr and Albert Einstein concerned language.[13] Bohr primarily thought in words, Einstein in images. For example, Bohr wrote that '[W]e can by no means dispense with those forms of perception which colour our whole language and in terms of which all experience must ultimately be expressed.'[14] Bohr only considered

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[10] See Heisenberg's 'Introduction' in M. Born, *The Born–Einstein Letters* (tr. I. Born), New York, 1971, x; and A. Fine, *The Shaky Game: Einstein, Realism, and the Quantum Theory*, Chicago, 1986, chs. 2 and 3.

[11] Fine, op. cit. (10), 19.

[12] Fine, op. cit. (10), 34–5.

[13] Throughout this paper, I use the word 'language' in the narrow sense of words and descriptions as they are written or spoken, rather than as a general term for communication of any kind. Einstein and Bohr used the word 'language' in this sense in their own writings. Thus, 'language' here is different from, for example, visual pictures or mathematical formalism. See M. Rudwick, 'The emergence of a visual language for geological science, 1760–1840', *History of Science* (1976), 14, 149–95, for a discussion of non-verbal, visual languages in science.

[14] N. Bohr, *Atomic Theory and the Description of Nature*, New York, 1934, 5.

the forms of perception important because they allow people to discuss their experiences in words. 'Every scientist...is constantly confronted with the problem of objective description of experience...Our basic tool is, of course, plain language.'[15] Language was the fundamental tool for Bohr, because words are the key to communication. Indeed, Bohr gained notoriety for his meticulous attention to language, even outside scientific endeavours. It has been recounted that he wrote rough drafts of postcards before sending them, and usually required five to ten preliminary drafts of scientific papers before publication. Robert Crease and Charles Mann entitle their chapter about Bohr simply 'The Man Who Talked'.[16]

Einstein did not share Bohr's insistence upon the primacy of words. He instead believed that 'words or the language, as they are written or spoken, do not seem to play any role in my mechanism of thought. The physical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be "voluntarily" reproduced and combined.'[17] Einstein relegated words to subordinate status: words were 'sought after laboriously only in a secondary stage'.[18] In fact, he deeply distrusted language. Although Einstein conceded that language may be instrumental when dealing with 'so-called abstract concepts', he warned that this capacity 'turns language into a dangerous source of error and deception. Everything depends on the degree to which words and word-combinations correspond to the world of impression.'[19] For Einstein, visual imagery was what counted. Words and language were poor, and sometimes dangerous, substitutes.

Effects of the split concerning language versus imagery may be seen in each physicist's first major trilogy of papers: Einstein's three celebrated 1905 papers, concerning light quanta, Brownian motion, and special relativity, are very brief. There is no unnecessary fanfare, for example, surrounding his famous dismissal of the ether as merely

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[15] N. Bohr, *Atomic Physics and Human Knowledge*, New York, 1958, 67.

[16] See R. Crease and C. Mann, *The Second Creation: Makers of a Revolution in Twentieth-Century Physics*, New York, 1986, 20–1; and A. Pais, *Niels Bohr's Times in Physics, Philosophy, and Polity*, Oxford, 1991, 102–3. Many Bohr scholars have split over the primacy of language in Bohr's personal approach to science, as presented here. Whereas Jan Faye, Henry Folse and Mara Beller have expressed reservations (in personal communications) about the degree to which Bohr's personal approach to physics relied upon semantic-linguistic considerations, Edward MacKinnon, Catherine Chevalley and John Honner have portrayed Bohr's work, in Honner's words, in terms of 'the relationship...between word and world, and between language and fact' (J. Honner, *The Description of Nature: Niels Bohr and the Philosophy of Quantum Physics*, New York, 1987, 7. See also E. MacKinnon, 'Bohr and the realism debate', in *Niels Bohr and Contemporary Philosophy* (ed. J. Faye and H. Folse), Dordrecht, 1994, 279–302; and C. Chevalley, 'Niels Bohr's words and the Atlantis of Kantianism', in ibid., 33–56). It is clear that Bohr was interested in communication from the start of his career, and in my interpretation, his emotional preference for working with groups came in tandem with a deep-seated interest in the role of language in science. He made public pronouncements about the role of language more frequently following the 1935 paper by Einstein, Podolsky and Rosen (discussed below), but the methodological roots of his semantic orientation may be traced earlier than his post-1935 work.

[17] Letter from Einstein to Jacques Hadamard, printed in Appendix II of J. Hadamard, *The Psychology of Invention in the Mathematical Field*, Princeton, 1945, 142–3. Also quoted in G. Holton, *Thematic Origins of Scientific Thought*, 2nd edn, Cambridge, Mass., 1988, 386.

[18] Einstein to Hadamard, in Hadamard, op. cit. (17), 142–3. Also quoted in A. Miller, *Imagery in Scientific Thought: Creating 20th-Century Physics*, Boston, 1984, 221.

[19] A. Einstein, 'The common language of science', in *Ideas and Opinions*, 2nd edn (ed. C. Seelig), 1982, 335–6.

'superfluous'.[20] Einstein's distrust of language prevented him from overindulging in it. Bohr's Trilogy of 1913 concerning atomic structure, on the other hand, is marked by long-windedness, extending three times the necessary length, according to Ernest Rutherford. An amusing exchange took place between Rutherford and Bohr regarding Bohr's 1913 papers: every time Rutherford told Bohr to shorten his papers prior to publication, Bohr answered with additions and apologies.[21]

The difference in orientation between Einstein and Bohr was also reflected in how they worked with others. Bohr emphasized language for communication, because he preferred to work with people. He was particularly influenced by his relationship with his brother Harald, as Henry Folse explains: 'From childhood the two brothers learned to express and sharpen their ideas in vigorous dialogue.'[22] One year after receiving his professorial appointment in Copenhagen, Bohr began petitioning for the establishment of an Institut for teoretisk Fysik in 1917, when he was just thirty-two years old.[23] He sought to create an environment in which theoretical physics could be developed 'in vigorous dialogue'. Although Abraham Pais notes that Bohr's most important scientific papers all bear his name alone, his style of work involved nearly constant communication with fellow physicists.[24] This communication continued throughout the actual composition of Bohr's papers, which he dictated to willing scribes, usually either his wife or young physicists from the institute. All of Bohr's scientific work was introduced into the world by constant verbal communication. To Bohr, language and community were essential for science.

Einstein, however, has been characterized by a willing apartness.[25] Unlike Bohr, Einstein 'did not create... what you might call a school... [T]he intensity of his collaboration with a few young people went hand in hand with a relative isolation.'[26] Einstein's emphasis upon imagery coupled with his preference for solitary thinking, unhampered by the distraction and deception brought by language-dependence and constant communication. Indeed, he wrote that after the age of twelve he developed a 'skeptical attitude towards the convictions which were alive in any specific social environment – an attitude which has never again left me.'[27] Whereas Bohr could work only in a social environment of friends and colleagues with whom he could talk about physics, Einstein remarked in 1930 on his own

> pronounced lack of need for direct contact with other human beings and human communities. I am truly a 'lone traveller' and have never belonged to my country, my home, or even my

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20 A. Einstein, 'Zur Elektrodynamik bewegter Körper', reprinted in *Albert Einstein's Special Theory of Relativity* (ed. A. Miller), Reading, Mass., 1981, 392.

21 The correspondence between Rutherford and Bohr regarding these papers is reprinted in *Niels Bohr Collected Works: Volume 2: Work on Atomic Physics (1912–17)* (ed. V. Hoyer), Amsterdam, 1981, 577–89. See Moore, op. cit. (4), 60–3.

22 H. Folse, *The Philosophy of Niels Bohr: The Framework of Complementarity*, New York, 1985, 32.

23 See Pais, op. cit. (16), 168–72, and Moore, op. cit. (4), 96–9.

24 Pais, op. cit. (16), 225.

25 Pais, '*Subtle Is the Lord...*', op. cit. (8), 35, 355; Pais, op. cit. (16), 227.

26 Peter G. Bergmann, 'Working with Einstein' Panel Discussion, reprinted in H. Woolf (ed.), *Some Strangeness in the Proportion: A Centennial Symposium to Celebrate the Achievements of Albert Einstein*, Reading, Mass., 1980, 479.

27 Einstein, op. cit. (1), 5.

> immediate family with my whole heart. In the face of all these ties I have never lost a sense of distance and a need for solitude – feelings that increase with the years.[28]

Once in 1954 Einstein was asked to comment by the Guggenheim Memorial Foundation on a grant request they received from a young applicant who wished to study theoretical physics in England. Einstein replied that the proposed topics of study seemed 'reasonable as efforts', although he did not consider the trip to England necessary: 'After all everybody has to do his thinking alone.'[29] Pais, who worked closely with both Einstein and Bohr, has characterized their difference this way: '[I]t was [Einstein's] deepest need to think separately, to be by himself. Bohr, on the other hand, craved togetherness, in life and in thought.'[30]

Bohr's and Einstein's varying emphases upon language were related to another difference of personal temperament: their varying trust of mathematics. Bohr's style of conducting science downplayed the use of mathematics. His published papers characteristically contain few equations: in fact, his entire published scientific *œuvre* contains on average less than one equation for every two pages of text.[31] His style consisted instead of *describing* problems and solutions with words. Thus, in the Bohr–Kramers–Slater paper of 1924, Bohr attempted to talk the new interpretation of radiation into place: the twenty-page paper contains only the single elementary formula $h\nu = E_1 - E_2$.[32] Similarly, in his first response to the Einstein–Podolsky–Rosen paper criticizing quantum mechanics, Bohr left their mathematical argument alone and attacked the assumptions made rather than the equations used in their argument.[33] Paul Dirac worked at Bohr's Copenhagen institute in 1926, and soon noticed Bohr's unmathematical orientation:

> People were pretty well spellbound by what Bohr said... While I was very much impressed by [him], his arguments were mainly of a qualitative nature, and I was not able to really pinpoint the facts behind them. What I wanted was statements which could be expressed in terms of equations, and Bohr's work very seldom provided such statements.[34]

Werner Heisenberg echoed Dirac's assessment, noting that Bohr 'never looked on the problems from a mathematical point of view'.[35] Bohr preferred to use language as his basic tool, rather than mathematics.

Einstein instead held the creative power of mathematics in high regard. Whereas language was considered a source of distraction and possible deception, Einstein lauded the

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28 Quoted in Hoffman, op. cit. (4), 253.

29 Letter from Einstein to Henry Allen Hoe at the John Simon Guggenheim Memorial Foundation, 28 November 1954. Einstein Archives, Box 6, #6-056; copies in the Seeley G. Mudd Manuscript Library, Princeton University, Princeton, New Jersey.

30 Pais, op. cit. (16), 227.

31 This approximate value comes from a survey of the resources compiled in the *Niels Bohr Collected Works* volumes.

32 N. Bohr, H. Kramers and J. Slater, 'The quantum theory of radiation', reprinted in *Sources of Quantum Mechanics* (ed. B. L. van der Waerden), New York, 1967, 162.

33 See N. Bohr, 'Can quantum-mechanical description of physical reality be considered complete?', *Physical Review* (1935), 48, 696–702.

34 P. A. M. Dirac, *History of Twentieth Century Physics*, 109, as quoted in Pais, op. cit. (16), 295.

35 Werner Heisenberg, interview conducted by Thomas S. Kuhn, 30 November 1962, p. 14 of transcript; copies in the American Institute of Physics Niels Bohr Library, New York, and other repositories of the Archives for the History of Quantum Physics (AHQP-AIP). Cf. Folse, op. cit. (22), 41–2.

role of mathematics in an article entitled 'On the method of theoretical physics': 'I am convinced that we can discover by means of purely mathematical constructions the concepts and the laws connecting them with each other, which furnish the key to the understanding of natural phenomena... Experience may suggest the appropriate mathematical concepts...[b]ut the creative principle resides in mathematics.'[36] To Einstein, mathematics fitted well with his own imagery-orientation. His preference for solitary thinking incorporated visualizable mathematical models rather than community conversation. Instead of agreeing with Bohr that language is the basic tool for science, Einstein believed 'that beautiful mathematics is the language of fundamental physics'.[37]

Bohr and Einstein on 'reality'

Bohr's emphasis upon language shaped his approach to ontology. Consider, for example, his statement that 'We are suspended in language in such a way that we cannot say what is up and what is down. The word "reality" is also a word, a word which we must learn to use correctly.'[38] Bohr was interested in objective description of physical phenomena, in keeping with his emphasis upon language and communication in science. This semantic temperament led Bohr to focus upon epistemology: how do we gain and express knowledge about the world around us? We learn about the universe, argued Bohr, by interacting with it. Objective description of phenomena requires that the phenomena be objects of possible experience or observation. Yet this entails that observation-independent reality must escape our powers of objective description. Therefore the proper meaning of the words 'physical reality', concluded Bohr, must refer to the 'content of an objective account of physical experience'.[39]

Bohr's attention to the limits of objective description motivated such famous remarks as: 'There is no quantum world. There is only an abstract quantum physical description.'[40] Critics have seized upon statements such as this one as evidence of Bohr's anti-realism. For example, Stanley Jaki claims that 'Bohr abolished the ontological reality of the universe itself' with the above quotation.[41] Yet the key word in Bohr's remark is 'quantum'. Although our abstract theoretical descriptions might fail to capture the observation-independent world, the world exists none the less. In other words, Bohr never doubted the ontological reality of the universe itself, only the extent of our epistemic access to the real universe.[42] His language orientation led him to dismiss attempted visualizations and descriptions of observation-independent reality as useless 'abstractions' or 'idealizations'.[43] In this way, Bohr's position is reminiscent of Kant's famous dictum: we must leave the things in themselves as 'indeed real *per se*, but as not known by us'.[44]

To Bohr, what was interesting for science was not the fact of existence itself, but rather our abilities and limitations in describing it. This is why there are very few references in Bohr's writings to 'reality', while so much attention is paid to our interactions with the world. Tellingly, Bohr's outline for a 1949 lecture entitled 'The Notion of Complementarity and Physical Reality' consisted of the following entries:

1. Observational problem in atomic physics.
2. Interaction between objects under investigation and measuring instruments.
3. Complementary phenomena appearing under mutually exclusive conditions.
4. Limitation of pictorial description in atomic physics and of the ascription of ordinary physical attributes to atomic objects.
5. Indeterminacy relations and their interpretations.
6. Details of measuring problems in QM [quantum mechanics] and QED [quantum electrodynamics].
7. Question of completeness of the QM description of physical reality.[45]

Bohr's lecture about 'physical reality' concentrated upon *epistemological* challenges presented by quantum mechanics: each entry concerns our ability to learn about and describe microphysical phenomena by interacting with them.

Bohr's particular ontological position thus sprang from his language orientation: science, for Bohr, depended upon communicable objective descriptions of the world. We must 'learn to use [the word "reality"] correctly' – the meaningful elements of physical reality for the progress of science are those about which we may form objective descriptions. Such physically meaningful elements of reality are those with which we may interact. Therefore, to Bohr, the observation-independent universe must remain 'indeed real *per se*, but not known by us'.

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[36] A. Einstein, 'On the method of theoretical physics', in Seelig, op. cit. (19), 274.

[37] C. N. Yang, 'Einstein and the physics of the future' Panel Discussion, reprinted in Woolf, op. cit. (26), 501.

[38] Quoted in A. Petersen, 'The philosophy of Niels Bohr', in *Niels Bohr: A Centenary Volume* (ed. A. P. French and P. J. Kennedy), Cambridge, Mass., 1985, 302. Henry Folse rightfully cautions against placing too much emphasis upon Petersen's very linguistic portrayal of Bohr's philosophy: many of the quotations attributed to Bohr were not written down, but rather recalled by Petersen during a time when linguistic analysis was very popular (personal communication).

[39] N. Bohr, unpublished 'Post scriptum,' dated 13 August 1957. Niels Bohr Archive: Bohr Manuscripts, reel 22; copies in AHQP-AIP. This short article was intended to follow the reprint of his 'Discussion with Einstein on epistemological problems in atomic physics' in Bohr, op. cit. (15).

[40] Quoted in Petersen, op. cit. (38), 305.

[41] S. Jaki, *God and the Cosmologists*, Washington, DC, 1989, 138–9. Cf. Fine, op. cit. (10), 34, 124, where he dismisses Bohr as simply 'the nonrealist', and calls Bohr's response to the 1935 Einstein–Podolsky–Rosen paper 'textbook neopositivism'. Jan Faye's recent analysis also paints Bohr as an anti-realist. See J. Faye, *Niels Bohr: His Heritage and Legacy*, Boston, 1991.

[42] Several analysts of Bohr's philosophy of physics have attempted to demonstrate a possible compatibility between Bohr's ontological position and realism: cf. Folse, op. cit. (22), 222–60; Murdoch, op. cit. (9), 200–22; and W. Daniel, 'Bohr, Einstein and realism', *Dialectica* (1989), 43, 250–3. Yet this approach can lead to pitfalls. For example, Murdoch states that Bohr was partly a 'weak realist' (p. 216), an 'instrumental realist' (p. 222), and that he incorporated a 'pragmatist strain' (p. 231). This constant need to qualify each description illustrates the benefits of adopting Arthur Fine's stance of dropping 'isms' from the analysis (Fine, op. cit. (10), 9). This sentiment is evident in some of Henry Folse's recent work, in which he has explained that Einstein's and Bohr's confrontation will be 'misconstrued' if staged 'on the philosopher's battle plain of realism versus antirealism'. H. Folse, 'The Bohr–Einstein debate and the philosophers' debate over realism versus anti-realism', paper presented at the June 1992 Beijing Conference on Realism. For a brief look at questions of Bohr's ontological approach and modern particle physics, see D. Kaiser, 'Niels Bohr's conceptual legacy in contemporary particle physics' in *Niels Bohr and Contemporary Philosophy* (ed. J. Faye and H. Folse), Dordrecht, 1994, 257–68.

[43] Cf., e.g., the essays in Bohr, op. cit. (14); and Murdoch, op. cit. (9), 208.

[44] I. Kant, *Critique of Pure Reason* (tr. N. K. Smith), New York, 1929, 24 (Bxix–xx). See D. Kaiser, 'More roots of complementarity: Kantian aspects and influences', *Studies in History and Philosophy of Science* (1992), 23, 213–39. The Bohr–Kant question is also examined briefly in Honner, op. cit. (16).

[45] This outline is for the sixth lecture of Bohr's Gifford Lectures. The notes are dated 14 July 1949. Niels Bohr Archive: Bohr Manuscripts, reel 19; copies in AHQP-AIP.

Einstein also 'presupposed the objectively existing real world'.[46] Yet, unlike Bohr, Einstein maintained faith in our power to understand the real world, independently of our interactions and observations: 'Out yonder there was this huge world, which exists independently of us human beings and which stands before us like a great, eternal riddle, at least partially accessible to our inspection and thinking.'[47] Whereas Bohr's preoccupation with language and communication led him to distrust our powers of epistemological access to things in themselves, Einstein's flight from the 'chains of the "merely-personal"' led him to hold fast to the notion that we may know physical reality as it exists independently of merely human observations and interactions.[48] Thus he wrote in 1918: 'I believe with Schopenhauer that one of the strongest motives that leads men to art and science is escape from everyday life with its painful crudity and hopeless dreariness, from the fetters of one's own ever-shifting desires. A finely tempered nature longs to escape from personal life into the world of objective perception and thought.'[49] In keeping with his intentional isolation from human communities, Einstein's motives centred upon *perception* and *thought*, rather than language and communication.

This particular ontological position was influenced by Einstein's imagery orientation: solitary, concentrated ontological intuition, combined with visualizable mathematical models, allow us to understand the objective world and thereby escape the fetters of personal life.[50] Our images and models extend beyond what we actually observe, or can ever hope to observe directly. Consider, for example, the treatment in general relativity and cosmology of the space-time curvature of the universe itself. These sorts of visualizable geometrical construction have no dependence upon human observation or intervention. Einstein strove to include this ultimate reality, independent of what we observe, in our physical theories. It is in this sense that he wrote, 'Without the belief that it is possible to grasp reality with our theoretical constructions...there would be no science.'[51] The 'reality' that Einstein sought to grasp was not Bohr's restricted realm of observable and describable phenomena, but the sum total of observation-independent existence.

Einstein could not accept Bohr's attention to interactions with the world, to the exclusion of considering how the world exists independently of us. Rather than restricting the meaningful elements of 'physical reality' to our objective accounts of experience,

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[46] I. Rosenthal-Schneider, *Reality and Scientific Truth: Discussions with Einstein, von Laue, and Planck*, Detroit, 1980, 92. This and the following discussion of Einstein's ontological position, scientific goal and methodological approach to science all concern his outlook as it had developed and stabilized prior to the beginning of the debate, i.e. roughly by 1920. For descriptions of Einstein's earlier positions, cf. Fine, op. cit. (10), 12–25; Holton, op. cit. (17), 191–370; and G. Holton, *The Advancement of Science, and its Burdens*, New York, 1986, 57–76.

[47] Einstein, op. cit. (1), 5.

[48] Einstein, op. cit. (1), 5.

[49] A. Einstein, 'Principles of research', in Seelig, op. cit. (19), 225.

[50] Arthur Miller notes that visual thinking and realism were 'allied' in classical physics, and that Einstein's own particular 'predilection for visual thinking' reflected in many ways elements of Boltzmann's and Helmholtz's non-verbal styles. Miller, op. cit. (18), 48, 112 and 128. 'Intuition' here should be understood as 'mental visualization', rather than denoting mystical 'clairvoyant' qualities of Einstein's 'genius', as Banesh Hoffman repeatedly uses it throughout Hoffman, op. cit. (4).

[51] A. Einstein and Leopold Infeld, *The Evolution of Physics*, as quoted in B. Gregory, *Inventing Reality: Physics as Language*, New York, 1988, 185.

Einstein insisted that 'Physics is an attempt conceptually to grasp reality as it is thought independently of its being observed. In this sense one speaks of "physical reality".'[52] Bohr's insistence upon observation and interaction appeared to Einstein as nothing but an 'epistemology-soaked orgy'.[53] Einstein mocked Bohr's dependence upon language, writing to Schrödinger that 'the Talmudist philosopher whistles at "Reality" as a bugbear of naiveté, and accounts for both views [particle and wave] as only according to a different mode of expression'.[54] To Einstein, dismissing ontological quandaries as resulting merely from the words we choose was an example of the dangers and deceptions inherent in language. Rather than shying away from questions about the real observation-independent universe, he pushed for a rational exploration of this realm. His ontological position grew from his dependence upon imagery and mathematics: 'physical reality' was not limited by the caprices of human communication, so neither should our studies of it be. Visualizable mathematical models thus allow us to escape the 'chains of the "merely-personal"'.

Bohr and Einstein each developed distinct interpretations of reality, that is, they both came to embrace particular ontological positions and attitudes. Their separate positions cannot be captured by philosophical labels. It is deceptive simply to cast Bohr and Einstein as ontological antipodes, with Bohr as some type of 'anti-realist' and Einstein as a 'realist'. Both Einstein and Bohr shared the primary realist tenet, as outlined by Arthur Fine, of belief in the *existence* of 'entities with relations and properties that are to a large extent independent of human acts and agents'.[55] They split on the second realist tendency concerning epistemological access to this fundamental reality: Bohr's semantic temperament made him restrict his dealings with 'physical reality' to the content of communicable, objective descriptions, whereas Einstein's imagery preference brought him to attempt to capture all of reality in his theories. In other words, their fundamental split over language versus imagery shaped their varying ontological positions.

The shaping of ontological positions by personal temperaments and preferences may be seen as an extension of Arthur Fine's 'motivational realism'. Fine analyses Einstein's realism and determines that his 'realism is not the robust metaphysical doctrine that one often associates with that label'.[56] Einstein's ontological position 'does not mark a set of beliefs about "reality"...It is not adequately expressed by any set of beliefs about the world, nor even by the injunction to pursue realist theories.'[57] Rather, Einstein's realist tendencies reflected the most motivationally appealing means of harmonizing his 'religious' faith in the 'rational nature of reality insofar as it is accessible to human reason',[58] with his personal imagery orientation and taste for mathematics. As Einstein himself perceived

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[52] Einstein, op. cit. (1), 81. Also quoted in Fine, op. cit. (10), 94.

[53] Quoted in Fine, op. cit. (10), 94.

[54] Letter from Einstein to Erwin Schrödinger, 19 June 1935. Einstein Archives, Box 28, #22-047: 'Der talmudische Philosoph aber pfeift auf die "Wirklichkeit" als auf einen Popanz der Naivität und erklärt beide Auffassungen als nur der Ausdrucksweise nach vershieden.' This letter is also quoted, with a different translation, in Fine, op. cit. (10), 36.

[55] Fine, op. cit. (10), 137.

[56] Fine, op. cit. (10), 105.

[57] Fine, op. cit. (10), 111.

[58] Letter from Einstein to Maurice Solovine, 1 January 1951, reprinted and translated in M. Solovine (ed.), *Albert Einstein: Letters to Solovine*, 2nd edn, New York, 1987, 118–21.

it, pursuit of realist theories, not limited to human observations, 'beckoned like a liberation' and promised 'inner freedom and security in devoted occupation with it'.[59]

A similar motivational drive, however, resulted in a very different personal ontology for Bohr. Bohr's depiction of 'physical reality' as the content of an objective account of physical experience represented his attempt to harmonize his language- and communication-dependence with his Kantian separation of objects as knowable and unknowable according to their possibility of experience.[60] Rather than attempting to escape the 'chains of the "merely-personal"', Bohr's ontology sought to embrace human interaction, and promised 'inner freedom and security' in science pursued 'in vigorous dialogue'. In other words, Einstein's and Bohr's ontological positions were shaped and forged by their resonance with other personal temperaments and cognitive orientations. Personality differences thus ramified throughout their individual interpretations of reality. These differences further carried over into Bohr's and Einstein's scientific goals.

THE SCIENTIFIC GOALS OF BOHR AND EINSTEIN

Bohr's scientific goal of *unambiguous communication* followed from his semantic interpretation of reality. Bohr used one of his favourite phrases to explain his notion of the task of science: 'What is it that we human beings ultimately depend on? We depend on words. *We are suspended in language.* Our task is to communicate experience and ideas to others. We must strive continually to extend the scope of our description, but in such a way that our messages do not thereby lose their objective or unambiguous character.'[61] In the previous section we noted Bohr's use of the phrase 'we are suspended in language' when describing his ontological position. His repetition of the phrase here, when discussing his scientific goal, demonstrates how tightly bound together his ontological disposition and his views of the tasks of science really were.

We have already seen that science for Bohr depended on language and communication, and not on abstract visualizations of unobservable nature. Bohr brought this sentiment out explicitly when discussing his goal for physics: 'It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature.'[62] Similarly, 'Our task is not to penetrate into the essence of things, the meaning of which we don't know anyway, but rather to develop concepts which allow us to talk in a productive way about phenomena in nature.'[63] In short, Bohr needed other people; the study of physics could only exist for him in a community setting. Yet the community could only function with unambiguous language. Thus Bohr perceived the establishment of unambiguous communication to be the goal of science.

Einstein did not subscribe to Bohr's ideas about the tasks of physics. Contrary to Bohr's statement that the task of physics is *not* to find out 'how nature is', Einstein remarked that 'What we call science has the sole purpose of determining what is.'[64] His ontological position likewise shaped his own scientific goal: he believed that all of reality was open to rational consideration, guided by visualizable mathematical models. The ultimate goal of science for Einstein was to be able to bring all of these rational investigations into a single unified *Weltbild.* That is, Einstein believed that the task of physics was to pursue a *unified understanding of the cosmos*: 'The supreme task of the physicist is to arrive at those universal elementary laws from which the cosmos can be built up by pure deduction.'[65] This unified understanding, for example, aimed to 'succeed in uniting quantum theory with electrodynamics and mechanics in a single logical system'.[66] Einstein actively pursued such unified theories from 1920 until his death in 1955, long before the contemporary efforts with 'Grand Unified Theories'.[67] Einstein's goal for science was axiomatization rather than communication. Unlike Bohr's, Einstein's very private goal depended upon clear pictures in one's own mind, and not upon talking with one's neighbour; recall his 'skeptical attitude' towards 'any specific social environment'. In this light, it is not surprising that Einstein described his ideal professional occupation to be a lighthouse keeper:[68] undisturbed by communal distractions, he would be able to pursue his theoretical physics and purify the foundations of his *Weltbild.*

Einstein and Bohr developed general methodological schemes in accordance with their separate scientific goals. It was at this 'public science' level where the actual conflict of the Einstein–Bohr debate became apparent. Yet Einstein's and Bohr's scientific work at the methodological level arose from their separate ontologies and scientific goals, and thus was very much grounded in their own personal temperaments.

BOHR'S AND EINSTEIN'S METHODOLOGICAL APPROACHES TO PHYSICS

Methodological doctrines

Bohr's task was to guarantee that the quantum realm remained describable. Heisenberg explained how he learned this from Bohr: '[Y]ou have to cover the experimental situation by means of concepts which fit... [T]he primary thing is here that you must find the words and the concepts to describe a funny situation in physics which is very difficult to understand.'[69] The quantum experiments, through which one interacted with and learned about quantum phenomena, necessarily depended upon macroscopic 'classical' apparatus

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[59] Einstein, op. cit. (1), 5.

[60] Cf. Kaiser, op. cit. (44).

[61] Quoted in Petersen, op. cit. (38), 301. Emphasis added.

[62] Quoted in Petersen, op. cit. (38), 305.

[63] Quoted in Pais, op. cit. (16), 23.

[64] Letter from Einstein to Solovine, 1 January 1951, reprinted and translated in Solovine, op. cit. (58), 118–21.

[65] Einstein, op. cit. (49), 226. Both Gerald Holton and Arthur Fine have noted that the title of this essay has been poorly translated: the original 'Motiv des Forschens' stands closer to 'Motives for research' than to the official translation as 'Principles of research'. Einstein's use of the word 'motives' enhances the notion that he perceived science as a very personal endeavour. See Fine, op. cit. (10), 109.

I do not mean to imply any sort of social or group agreement or solidarity by the term 'unified'. Rather, 'unified' for Einstein meant that the various principles are themselves mutually woven together into a single coherent *Weltbild*. This unification was a very private endeavour. My thanks to Rich Kremer for pointing out this possible misinterpretation.

[66] Einstein, op. cit. (49), 227. Cf. G. Holton's chapter 'Einstein's model for constructing a scientific theory', in Holton, op. cit. (46), 28–56.

[67] See, e.g., Pais, op. cit. (25), ch. 17.

[68] Cf. Klein, op. cit. (7), 320 and Hoffman, op. cit. (4), 170.

[69] Werner Heisenberg, interview conducted by Thomas S. Kuhn, 30 November 1962, p. 14 of transcript; copies in AHQP-AIP.

and experimental arrangements. Bohr maintained, therefore, that physicists could only retain the clarity of classical physics if they adopted its language to discuss quantum phenomena. These were the 'concepts which fit'. That is, Bohr sought to fulfil his scientific goal of unambiguous communication by grounding discussion of quantum phenomena 'in unambiguous language with suitable application of the terminology of classical physics'.[70]

Yet quantum phenomena do not behave like classical phenomena: by setting discussion of the quantum realm in the language of classical physics, we must be prepared to accept new interconnections between the classical concepts. This is the heart of Bohr's philosophy of complementarity. He explained that in the quantum realm we must 'adopt a new mode of description designated as complementary in the sense that any given application of classical concepts *precludes the simultaneous use* of other classical concepts which in a different connection are *equally necessary for the elucidation* of the phenomena'.[71] We must use classical concepts in order to discuss the quantum realm objectively, but these concepts now stand in a new relationship to one another. The wave–particle duality of light is one well-known example of combining mutually exclusive descriptions to produce a complete explanation of phenomena.[72]

Bohr's complementarity reveals his general methodological doctrine: we must retain those classical concepts closest to experience, because these concepts allow physicists to talk about experiments. Yet Léon Rosenfeld explains that like 'Picasso's art...these concepts no longer occur in their familiar interconnections'.[73] Bohr urged that we limit the applicability of the general principles of classical physics, which had organized and related the various classical concepts in the macroscopic non-relativistic realm. For example, at one point in 1924, Bohr argued that whereas the concept of 'energy' helped physicists discuss microphysical experiments, the abstract general principle of 'conservation of energy' no longer held strict validity, and its application should be limited in the quantum realm.[74] Although the Bohr–Kramers–Slater paper was soon shown to disagree with experiments conducted by Geiger and Bothe, Bohr's treatment of conservation laws *qua* general principles reflected his methodological doctrine. Rosenfeld characterizes this methodology by writing that 'we rise higher in the realm of rational knowledge when we get rid of some metaphysical tether'.[75]

Einstein's methodological doctrine, on the other hand, emphasized the importance of general principles. This followed from his scientific goal of axiomatization: he aimed to 'represent the multitude of concepts and propositions...close to experience, as...logically deduced from a basis'.[76] Unlike Bohr, who gave priority to those concepts 'close to experience', Einstein strove to deduce these experiential concepts as *consequences* of the more fundamental basis of physical principles. Consider his reaction to Emmy Nöther's theorem, which demonstrated the connection between symmetries and associated conservation principles: 'I am impressed that one can oversee [übersehen] these things from such a general standpoint.'[77] Einstein's lighthouse-keeper metaphor shines through again: the beacon of axiomatic physical principles illuminates physical experience, and allows the lone physicist to 'oversee' particular experiences from the standpoint of general principles.

This discussion points to a limitation of Arthur Fine's analysis with regard to assigning the label of 'conservative' to Bohr rather than Einstein. In fact, *both* Einstein and Bohr were equally 'conservative', or indeed equally 'radical', but in different ways. Bohr was adamant about maintaining those concepts close to experience, upon which the classical language was based. Presumably Bohr's insistence upon retaining the classical language is the target of Fine's comment that 'It was Bohr who balked at the idea that one might give up the classical concepts...it is Bohr who emerges the conservative, unwilling (or unable?) to contemplate the overthrow of the system of classical concepts.'[78] Yet Einstein remained equally adamant about retaining (classical) general principles, the axiomatic basis from which he considered Bohr's beloved experiential concepts to be deduced. Whereas Einstein agreed with Erwin Schrödinger that 'the concepts p, q [momentum, position] *will have to be given up*, if they can only claim such a "shaky" meaning' in the light of the uncertainty principle,[79] Bohr argued equally radically that we must 'get rid of some metaphysical tether' in the form of general principles. The methodological doctrines of Einstein and Bohr each embodied strict adherence to one kind of classical entity and a willingness to discard a different kind of classical entity – neither was more 'conservative' than the other.

Einstein's and Bohr's methodological doctrines influenced their respective criteria for judging scientific theories. The different personal temperaments of the two physicists surfaced in their separate considerations of theoretical adequacy. Their methods clashed over the specific case of whether or not quantum mechanics was worthy of acceptance as an adequate physical theory. This conflict, arising at its core from a difference of personality, touched off the thirty-year Einstein–Bohr debate.

Correspondence principle versus physical plausibility

Bohr's methodological doctrine of retaining elementary concepts and revising the general principles relating them informed the way he judged new theories. Bohr expressed this in terms of his 'correspondence principle': '[T]he necessity of making an extensive use...of

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[70] N. Bohr, 'Discussion with Einstein on epistemological problems in atomic physics', in *Albert Einstein: Philosopher-Scientist* (ed. P. A. Schilpp), Evanston, Ill., 1949, 210. Also quoted in Holton, op. cit. (17), 103.

[71] Bohr, op. cit. (14), 10. Emphasis added.

[72] For more on complementarity, see especially Folse, op. cit. (22); Murdoch, op. cit. (9); and Kaiser, op. cit. (44).

[73] L. Rosenfeld, 'Strife about complementarity', in *The Selected Papers of Léon Rosenfeld* (ed. R. S. Cohen and J. J. Stachel), Boston, 1979, 480.

[74] Bohr, Kramers and Slater, op. cit. (32).

[75] Rosenfeld, op. cit. (73), 476.

[76] Einstein, 'Physics and reality', in Seelig, op. cit. (19), 294. Don Howard's investigation of Einstein's disapproval of quantum mechanics highlights two specific examples of Einstein's general methodological approach. Howard's treatment, like Fine's, emphasizes Einstein's reluctance to give up the general principles of 'locality' and 'separability'. (Cf. D. Howard, 'Einstein on locality and separability', *Studies in History and Philosophy of Science* (1985), 16, 171–201.) For Einstein, 'locality' and 'separability' were two (axiomatic) general principles which should not be sacrificed in the name of complementarity.

[77] Letter from Einstein to David Hilbert, 24 May 1918. Einstein Archives, Box 15, #13-125. 'Es imponiert mir, dass man diese Dinge von so allgemeinem Standpunkt übersehen kann.'.

[78] Fine, op. cit. (10), 19.

[79] Letter from Einstein to Schrödinger, 31 May 1928. Reprinted and translated in K. Przibram (ed.), *Letters on Wave Mechanics* (tr. M. Klein), New York, 1967, 31. Emphasis added. Also quoted in Fine, op. cit. (10), 18.

the classical concepts, upon which depends ultimately the interpretation of all experience, gave rise to the formulation of the so-called correspondence principle which expresses our endeavors to *utilize all the classical concepts* by giving them a suitable quantum-theoretical *re-interpretation*.'[80] Bohr's correspondence principle stated that if a new theory yielded the same numerical predictions as an accepted theory under specific limiting conditions, then the new theory may be said to 'correspond' to the older established theory. This correspondence meant that the new theory warranted further consideration; that is, the theory had met Bohr's basic requirement for theoretical adequacy.

The specific limiting conditions that Bohr spoke of included two different situations. The first was that the theories yielded the same answers within the domain of the older theory, even if the new theory operated within a larger scope, that is, was more general. Or the specific limiting conditions might mean that the two theories produced the same results after assigning certain values to theoretical constants. For example, the correspondence, as Bohr saw it, between quantum physics and classical physics may be written:

$$\lim_{h\to 0}[\text{quantum physics}] = [\text{classical physics}].^{81}$$

Correspondence in this fashion therefore does not mean that the theories are identical, or even similar. Rather, it merely requires that the new theory be what Bohr termed a 'natural generalisation' of the older theory.[82] The general principles that the two theories hold and the mathematical formalism with which they operate might be very different from each other. Consider, for instance, quantum theory's discrete energy spectra, in comparison with classical mechanics' energy continuum, or Heisenberg's matrix mechanics versus differential calculus.

Bohr's correspondence principle therefore implicitly contained his methodological doctrine: correspondence between two theories makes no requirements about the continuity of general principles between the theories. Instead, it merely requires that the new theory be expressed in the same terms as the older theory, to allow comparison of their predicted results for a particular problem. As Dugald Murdoch notes, the new theory need *not* be 'logically derivable from the former'.[83] Or as Rosenfeld has remarked, the correspondence principle, like Bohr's complementarity, encourages us to 'get rid of some metaphysical tether'.

Bohr formalized his two criteria for theoretical adequacy, which followed from his correspondence principle. He wrote that the only two reasons to deem a logically consistent theory inadequate were 'the departure of its consequences from experience or... proving that its predictions did not exhaust the possibilities of observation'.[84] In other words, if the new theory successfully corresponded to the established theories and agreed with empirical observations, then it should be accepted as deserving further theoretical consideration and experimental testing. The new theory must be internally logically consistent, but need not be logically related to previous theories.

Einstein believed with Bohr that the failure of a new theory to meet either of these criteria would make the theory inadequate, but he did not believe that these were the *only* two criteria by which to make such a judgement. That is, Einstein accepted the asymptotic agreement of the correspondence principle to be a necessary condition, but he did not believe that it was sufficient. What was lacking, for Einstein, was any concern for the general physical principles of the new theories. Einstein emphasized general principles because of their role in the axiomatization of physics: if all of physics was to be derivable from a basis of general axioms, we must take care that new physical theories maintain the same general principles as the existing accepted theories. Only in this way can the new theories contribute to a unified understanding of the world.

Bohr noted the consequences of their diverging viewpoints on theoretical adequacy for the specific case of quantum mechanics:

> Notwithstanding the most suggestive confirmation of the soundness and wide scope of the quantum-mechanical way of description, Einstein nevertheless... expressed a feeling of disquietude as regards the *apparent lack of firmly laid down principles* for the explanation of nature, in which all could agree. From my viewpoint, however, I could only answer that, in dealing with the task of bringing order into an entirely new field of experience, we could *hardly trust in any accustomed principles*, however broad, apart from the demand of *avoiding logical inconsistencies* and, in this respect, the mathematical formalism of quantum mechanics should surely meet all requirements.[85]

Einstein's 'disquietude' came from Bohr's abandonment of 'accustomed principles'. Einstein agreed with Bohr that quantum mechanics was itself logically consistent: 'It is not my opinion that there is a logical inconsistency in the quantum-theory itself.' The problem was that 'quantum theory is not compatible with certain principles the convincing-power of which is independent of the present quantum theory'.[86] Quantum mechanics cut loose too much 'metaphysical tether' for it to fit into Einstein's *Weltbild*. This is why Einstein required more from new theories than simply an avoidance of internal logical inconsistencies.

Einstein added a third criterion by which a new theory may be deemed inadequate. I call this Einstein's 'physical plausibility' criterion.[87] To be physically plausible, a new theory

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[80] Bohr, op. cit. (14), 8. Emphasis added. Cf. Murdoch, op. cit. (9), 37–9; and Folse, op. cit. (22), 100–1, 128–9.

[81] See R. Serway, C. Moses and C. Moyer, *Modern Physics*, New York, 1989, 94. In this text, the limit expression is given for $n \to \infty$, instead of $h \to 0$ as I have written. The choice of variables here evinces the difference between the two types of specific limiting conditions, i.e. allowing h (Planck's constant) to tend to zero involves the assignment of certain values to theoretical constants, whereas n (principal quantum number) $\to \infty$ is an example of the restriction to certain limiting domains of application. Either way, the use of the mathematical limit notation seems to me to be the best way of expressing the asymptotic agreement requirement of Bohr's correspondence principle.

[82] N. Bohr, 'On the quantum theory of line-spectra', in *Sources of Quantum Mechanics* (ed. B. L. van der Waerden), New York, 1967, 116.

[83] Murdoch, op. cit. (9), 40.

[84] Bohr, op. cit. (70), 229.

[85] Bohr, op. cit. (70), 228. Emphasis added.

[86] Letter from Einstein to L. Cooper, 31 October 1949. Einstein Archives, Box 9, #8-411.

[87] This term is inspired by David Bohm's protests against Einstein's physical plausibility criterion: 'I have the feeling that you do not wish to accept this point of view [regarding the measurement of an electron's momentum] on the grounds that you regard it as *implausible*... It is not desirable to require that [a theory] fit your own *personal standards of plausibility*, which after all, depend very much on our own particular and limited experience.' Letter from David Bohm to Einstein, undated ('probably 1950/51'). Einstein Archives, Box 8, #8-001. Emphasis added.

had to extend the scope of physics in accordance with the established general principles and physical axioms. For Einstein, this meant that physical intuition, arising from his personal imagery temperament, could support the logical deduction of the whole of physics.

As Arthur Fine has written, the Einstein–Bohr debate that arose over the acceptance or rejection of quantum mechanics 'was not over accommodating experimental facts, or understanding the new mathematics of the quantum formalism, or taking in new physical ideas, or the like. It was a dispute at the level of methodology over what processes of concept formation are progressive; i.e., constitute fundamental scientific advance.'[88] This 'dispute at the level of methodology' was rooted in the personal contexts informing Einstein's and Bohr's positions. Einstein himself noted this, writing that 'Whether somebody thinks a plan promising or not depends entirely from the judge's guesses about the future development.'[89] Similarly, Bohr concluded his 1949 review article of his discussions with Einstein by commenting upon the 'many obstacles for mutual understanding as regards a matter where approach and background must influence everyone's attitude'.[90]

Einstein on quantum mechanics: EPR and beyond

Quantum mechanics is marked by a departure from the general principles of previous theories: many of the general principles and conceptual interrelations of the previous theories no longer remain universally valid. Instead, these general principles remain applicable only under specific circumstances, in complementary relationships with other formerly general principles. For example, in quantum mechanics the principles of strict causality and space-time representation become complementary. A total explanation of phenomena must make use of both principles, but the explanation cannot use them simultaneously, because the conditions under which each principle is separately valid are mutually exclusive.[91] While Bohr accepted (and even promoted) this methodological characteristic of quantum mechanics, it is easy to see that Einstein would not.

In 1935 Einstein's growing 'disquietude' with quantum theory's departure from his methodological doctrine found expression in the now-famous article entitled 'Can quantum-mechanical description of physical reality be considered complete?'[92] For this paper Einstein collaborated with Boris Podolsky and Nathan Rosen, all of whom were working at the Institute for Advanced Study in Princeton. The authors ('EPR') aimed to demonstrate that quantum mechanics is an incomplete theory, and argued that it should be replaced with some new theory of the microphysical realm.[93] The EPR paper is most famous for its proposed *gedanken*-experiment. The authors alleged that measurements of one quantum system can instantaneously attribute reality to physical quantities of two non-commuting operators of a second spatially separated quantum system. That is, their *gedanken*-experiment would reveal both the momentum of a quantum system as well as its *simultaneous* position, a result strictly forbidden by Heisenberg's uncertainty principle. Within the framework of the entire argument, this negation of the uncertainty principle led to the conclusion that quantum mechanics is necessarily incomplete.

Arthur Fine highlights evidence from Einstein's correspondence with Erwin Schrödinger proving that Einstein did not in fact participate in the actual writing of the EPR paper: 'For reasons of language this [paper] was written by Podolsky after much discussion. Still, it did not come out as well as I had originally wanted; rather the essential thing was, so to speak, smothered by the formalism.'[94] As far as Einstein was concerned, the EPR paper did not explicitly address his methodological criticisms of quantum mechanics. The 'essential thing' that was smothered in the EPR paper was Einstein's physical plausibility criterion.

The first key to understanding Einstein's discontent is that he did not only consider quantum mechanics to be *incomplete*, but *fundamentally inadequate*. Deltete and Guy correctly summarize that Einstein 'believed, in short, that the quantum theory was... not the appropriate starting point for constructing the new theory he thought was needed'.[95] Quantum mechanics was inadequate to Einstein because of its break with the general principles of classical physics; it thus remained impossible to incorporate within the axiomatic basis of physics.

Before the publication of the EPR article, Einstein criticized the quantum theory in terms of his physical plausibility criterion. He granted that quantum mechanics by itself was 'logically unobjectionable,' although he could only attach to it a 'transitory importance... I still believe in the possibility of a model of reality – that is to say, of a theory which represents things themselves and not merely the probability of their occurrence.'[96] Sixteen years later the same impulse came through: 'Such an interpretation is certainly by no means absurd from a purely logical standpoint; yet there is hardly likely to be anyone who would be inclined to consider it seriously.'[97] Einstein required more from quantum mechanics than an avoidance of logical inconsistencies.

The inherent flaw of quantum mechanics lay for Einstein in its incompatibility with the axiomatic general principles. As he explained in his article 'Physics and reality', which

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[88] Fine, op. cit. (10), 22.

[89] Letter from Einstein to Henry Allen Hoe, 28 November 1954, Einstein Archives, Box 6, #6-056. Notes between Paul Ehrenfest and Einstein (undated, probably from the fifth Solvay conference, 1927) similarly reveal Einstein's constant awareness of 'future development'. Ehrenfest wrote to Einstein 'Don't laugh!' ('Lache nicht!'), to which Einstein replied, 'I laugh *only* at the naiveté [presumably of the proponents of quantum mechanics, the subject of the conference]. Who knows who will be laughing in the coming years.' ('Ich lache *nur* über die Naivotät. Wer weiss wer in einigen Jahren lacht.') Einstein Archives, Box 11, #10-153.

[90] Bohr, op. cit. (70), 239.

[91] See, e.g., W. Heisenberg, *The Physical Principles of the Quantum Theory*, New York, 1930, 65.

[92] A. Einstein, B. Podolsky and N. Rosen, 'Can quantum-mechanical description of physical reality be considered complete?', *Physical Review* (1935), 47, 777–80. Hereafter I will refer to this paper simply as 'EPR'.

[93] EPR, op. cit. (92), 777–80. Cf., e.g., Hooker, op. cit. (9); N. Rosen, 'Can quantum-mechanical description of physical reality be considered complete?', in *Albert Einstein: His Influence on Physics, Philosophy and Politics* (ed. P. C. Aichelburg and R. U. Sexl), Braunschweig, 1979, 57–68; Fine, op. cit. (10); M. Redhead, *Incompleteness, Nonlocality, and Realism*, New York, 1987, ch. 3; R. Deltete and R. Guy, 'Einstein's opposition to the quantum theory', *American Journal of Physics* (1990), 58, 673–83; and Kaiser, op. cit. (44).

[94] Letter from Einstein to Schrödinger, 19 June 1935. Einstein Archives, Box 28, #22-047. Portions of this letter are translated and reprinted in Fine, op. cit. (10), 35–6, from which the above text is quoted. Yet where Fine supplies 'paper', Einstein's actual referent is 'little treatise' ['kleine Abhandlung']. The adjective 'little' here might simply refer to the brevity of the EPR paper (four pages); but it could also mean 'petty', thereby adding weight to Einstein's derision of the EPR paper's 'smothering formalism'.

[95] Deltete and Guy, op. cit. (93), 679.

[96] Einstein, op. cit. (36), 275–6.

[97] A. Einstein, 'Reply to criticisms', in Schilpp (ed.) op. cit. (70), 671.

appeared less than one year after the EPR paper, quantum mechanics 'is apt to beguile us into error in our search for a uniform basis for physics'.[98] He expanded upon this idea:

> There is no doubt that quantum mechanics has seized hold of a good deal of truth, and that it will be a touchstone for any future theoretical basis, in that it must be deducible as a limiting case from that basis... However, I do not believe that quantum mechanics can serve as a *starting point* in the search for this basis, just as, vice versa, one could not find from thermodynamics (resp. statistical mechanics) the foundations of mechanics.[99]

The problem with quantum mechanics, to Einstein, was that it could not serve as an adequate axiomatic base for a unified programme in physics. The link is clear in his 1949 'Reply to criticisms': 'One arrives at very *implausible* theoretical conceptions, if one attempts to maintain the thesis that the statistical quantum theory is in principle capable of producing *a complete description* of an individual physical system... With this one would admit that, in principle, this scheme [quantum mechanics] *could not serve as the basis of theoretical physics*.'[100] The 'implausibility' of quantum mechanics stems from its inability to 'serve as the basis of theoretical physics', merely a symptom of which is its inability to 'produce a complete description'.

Einstein provided numerous expositions of his discontent with quantum mechanics; it is ironic that his best-known criticism is a paper which he did not write, and which smothered his underlying reasoning. Einstein's objections to quantum mechanics sprang from very personal sources. Quantum mechanics conflicted with Einstein's entire scientific mindset: the theory was not visualizable, in opposition to Einstein's imagery orientation.[101] The theory did not treat reality as Einstein interpreted it, but restricted its predictions to probabilities for the results of measurements and observations. He could not accept the limitation of physics to human intervention with nature, and wrote that 'My own opinion is... that we will return to the task to describe real phänomena in space and time (not only probabilities for possible experiment).'[102] A theory catering exclusively to people's possible experiments held no motivational value for a lone lighthouse keeper. Most important, quantum mechanics failed Einstein's physical plausibility criterion. Einstein expressed this objection immediately following the Göttingen theorists' extension of Heisenberg's matrix mechanics: 'I have been trying to grapple with the Born–Jordan model of the atom lately. I suppose that in some points it must be right but at present I cannot raise any great enthusiasm for it; *it will be a horrible creature to fit in to the rest of the world*.'[103] Quantum mechanics was fundamentally at odds with Einstein's entire personal approach to science.

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[98] Einstein, op. cit. (76), 315.

[99] Einstein, op. cit. (76), 319.

[100] Einstein, op. cit. (97), 671–2. Emphasis added.

[101] Bohr repeatedly remarked upon this aspect of quantum mechanics, describing, e.g., 'the extent to which renunciation of the visualization of atomic phenomena is imposed on us', and 'emphasiz[ing] how far, in quantum theory, we are beyond the reach of pictorial visualization' (Bohr, op. cit. (70), 222, 232). See Miller, op. cit. (18), especially for the differences between *Anschauung* and *Anschaulichkeit* in quantum theory: 'in the atomic domain visualization and visualizability are mutually exclusive... [whereas] in classical physics visualization and visualizability are synonymous'. Miller, op. cit. (18), 154.

[102] Letter from Einstein to Paul Bonofield, 18 September 1939. Einstein Archive, Box 6, #6-118-1.

[103] Letter from Einstein to Arthur S. Eddington, 22 January 1926. Emphasis added. Einstein Archive, Box 10, #9-288.

Quantum theory and complementarity

Bohr's first response to the EPR paper emerged five months later, in a paper with the same title.[104] He argued that EPR's *gedanken*-experiment could never be realized in practice: the two measurements, relating separately to a quantum system's position and momentum, require *different* 'experimental arrangements and procedures', so that they may *not* be combined under the guise of superseding the uncertainty principle. Furthermore, the two sets of experimental arrangements and procedures are themselves *mutually exclusive*, so that EPR's hypothetical simultaneous momentum and position measurements are beyond the realm of possible experience.[105] This merely pointed, for Bohr, to the complementarity of space-time representation and the conservation of momentum in the quantum realm, a necessary loosening of 'metaphysical tether'.

In other words, Bohr argued that it is not enough to associate the 'elements of physical reality' solely with observables such as position and momentum.[106] Bohr maintained that we must retain such classical concepts and terms as 'position' and 'momentum' in order to be able to discuss our real physical experiments. But because the concepts no longer share the same interconnections as they did in classical physics, we must treat their applicability more carefully. If our use of the classical terms is to remain valid, then we must include information regarding the real physical experimental arrangements and procedures. This Kant-like attention to the conditions and limits of our empirical knowledge sprang in part from his scientific goal of keeping the quantum realm describable in language.[107]

Seen in this light, the EPR authors were guilty of 'arbitrarily picking out... different elements of physical reality at the cost of... other such elements'.[108] Their failure to adopt the necessary revisions in our general principles led Bohr ultimately to dismiss the EPR argument years later: 'The whole idea is absolutely nothing when one gets into it.'[109]

Although Einstein's underlying discontent with quantum mechanics was not adequately represented in the EPR paper, Bohr's response to EPR implicitly addressed Einstein's own criticism. It was harmful for the progression of science, to Bohr, to require more of a new theory than correspondence with the older theories. As far as Bohr was concerned, quantum mechanics successfully united his personal interests and concerns for physics: the theory did not waste time attempting to 'penetrate into the essence of things' by blindly following worn-out general principles. Rather, it enabled physicists to talk 'in a productive way' and in familiar terms about new phenomena. In Bohr's mind, the acceptance of quantum mechanics by the physics community would supply a logically consistent framework to support continued unambiguous communication. In other words, quantum mechanics cohered with Bohr's general scientific goal and met his criteria for adequacy. Bohr was satisfied that quantum mechanics was an acceptable physical theory.

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[104] Bohr, op. cit. (33).

[105] Bohr, op. cit. (33), 699.

[106] Bohr, op. cit. (33), 699.

[107] Cf. Hooker, op. cit. (9), 168; and Kaiser, op. cit. (44).

[108] Bohr, op. cit. (33), 699.

[109] Interview with Niels Bohr, conducted by Thomas S. Kuhn, Aage Petersen and Eric Rüdinger, 17 November 1962, p. 11 of transcript; copies in AHQP-AIP.

CONCLUSIONS

The Einstein–Bohr debate reveals some roles which private factors may play in scientific activity, and highlights the degree to which scientists' personal temperaments shape the science they do. Even within the same basic environment and shared community, Albert Einstein and Niels Bohr approached scientific problems with fundamentally different personal beliefs and commitments about the goals of science and the qualities of a good scientific explanation. This split cannot be explained away as either 'marks of genius' or mere manifestations of social interests. While moving away from previous great-man tales of the 'battle of titans', the roots of the controversy refuse to be reduced entirely to any 'larger social context'. The debate thereby demonstrates the historian's need to consider the personal context of the controversy.

The personal context of the Einstein–Bohr debate reveals two very different approaches to physics. Bohr needed to pursue science in community settings, and remained fascinated by our suspension in language. In his mind, it was essential for the physics community to be able to '*talk* in a productive way about phenomena in nature', which translated for Bohr into a rigid adherence to the language of classical physics and a corresponding loosening of former general principles. Einstein, on the other hand, distrusted language and remained sceptical of social environments, insisting instead that 'everybody has to do his thinking alone'. Unifying principles and axioms, pursued via solitary visual-mathematical intuition, captured his attention, as reflected in his physical plausibility criterion. Quantum mechanics remained to Einstein a remnant of the fetters of mundane, everyday community life, and its break with general principles made it 'a terrible creature to fit in to the rest of the world'.

Bohr's and Einstein's personal approaches to science reflected more than intellectualized *Denkstile*.[110] The personal context instead reveals, to borrow a phrase from Jed Buchwald, a 'fractal model for history':[111] the underlying commitments to language or imagery, and community or isolation, were replicated throughout Bohr's and Einstein's respective ontological attitudes, scientific goals, methodologies, and criteria for judging theories. At its base, then, their conflict arose from varying *emotional* motivations: whereas Bohr came from a close-knit family that fostered group communication, Einstein characterized himself as a 'lone traveller', and remarked upon his 'lack of need for direct contact with other human beings and human communities'. Thus, the two physicists' approaches to physics were grounded in fundamentally different personalities.

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[110] A recent issue of *Science In Context* (1991), 4, 2, focuses on the somewhat problematic term 'style' as an explanatory tool in history of science. The collected articles debate the appropriateness of isolating various national, scholastic, and individual styles. (Cf. especially Anna Wessely's criticism of the use of 'style', in A. Wessely, 'Transposing "style" from the history of art to the history of science', *Science In Context* (1991), 4, 265–324.) To be helpful, descriptions of individuals' personal approaches to science in terms of 'style' must reflect their personal context: scientists' styles of work cannot be disembodied from their emotional commitments and motivations.

[111] J. Buchwald, 'Essay review of *Energy and Empire*', *BJHS* (1991), 24, 87. The fractal imagery testifies to the robustness of 'personality' as a historiographical tool. Its explanatory power derives from the close-knit *coherence* of an individual's pre-scientific and scientific activity. Whereas 'genius' was hoisted by older generations as a means of black-boxing the roots of an individual's scientific activity, investigations of 'personal context' open the black-box a little to reveal a constrained system of repeated patterns.

This difference in personality may help to explain why physicists have historically adopted Bohr's position, both by accepting quantum mechanics and by continuing his trend of working in groups, yet hang pictures of Einstein on their walls. Einstein's solitary lighthouse-keeper personality lends itself far more readily to a 'guru on the mountaintop' image, and posters of him characteristically include aphoristic quotations. Despite the ubiquity of quantum mechanics, it remains impossible to buy a poster of Niels Bohr.

In analysing the Einstein–Bohr debate, we may extend Helen Longino's work on scientists' 'evidential reasoning'. Longino incorporates the notion that there is no such thing as a theory–observation dichotomy; she argues that mere facts offer no data, and thus observations are always made within a theoretical context.[112] While not the direct causes of an individual's particular observations, a scientist's background beliefs and assumptions are necessary conditions for the observations to take place. Longino's analogy is the necessary presence of oxygen in the atmosphere for sparks to be created when two dry wooden sticks are struck together; although the oxygen does not itself cause the sparks, it is none the less a necessary condition for the sparks. In this way, Longino writes that individuals' subjective preferences, in the form of background beliefs, enter into scientific observations: all 'evidential reasoning' is dependent upon the interplay between observational data and the observing scientist's contextual background.[113]

The Einstein–Bohr debate illustrates an extension of Longino's analogy, revealing how individual scientists' personalities ramify throughout entire fractal patterns of beliefs, temperaments, orientations, motivations, goals and theories. These personal factors are present at every stage of scientific activity. In this way, an individual's scientific work is shaped and forged by his or her personality. Like the presence of oxygen, an individual's personal temperament is not the cause of particular theories. Rather, theories can only be dealt with by scientists in the framework of these personal temperaments. Scientists' private considerations form a necessary environment in which their scientific activity takes place. The scientist, as a person, cannot be divorced from the scientific work that he or she engages in.

Investigations of personal contexts must therefore supplement investigations of social contexts. Charles Rosenberg has addressed this need to view both the 'woods' and the 'trees'. The problem for history of science, as he sees it, is to integrate the social constructivist investigations of institutional, social and cultural aspects of science (the 'woods' or forest) with a consideration of the individual actors' 'perceptions and strivings' (the 'trees' making up the forest). He writes, for example: 'Institutions are not reducible to tables of organization or budget lines; they are made real by the perceptions, actions, and commitments of particular men and women who function within them ... Specific ideas and academic values exist ... not in some realm of disembodied cognition but in minds and

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[112] Ian Hacking, Peter Galison and Timothy Lenoir object to such theory-dominated accounts of science, and discuss the experimental and technological presuppositions of observations. Cf. I. Hacking, *Representing and Intervening*, New York, 1983; P. Galison, *How Experiments End*, Chicago, 1987; and T. Lenoir, 'Practice, reason, context: the dialogue between theory and experiment', *Science In Context* (1988), 2, 3–22. The present paper's emphasis upon theory stems from the nature of the Einstein–Bohr debate: both disputants agreed that quantum mechanics was more or less empirically corroborated.

[113] H. Longino, *Science as Social Knowledge*, Princeton, 1990, 40–4.

emotional priorities of particular individuals.'[114] Max Planck echoed this sentiment in a letter to Bohr in 1930: 'The highest court is in the end one's own conscience and conviction – that goes for you and for Einstein and every other physicist – and before any science there is first of all belief.'[115]

Thus, to paraphrase Einstein's remarks, social constructivism, like quantum mechanics, has no doubt 'seized hold of a good deal of truth': scientific activity is substantially shaped and constrained by the social environment in which it is practised. Yet this description by itself is not complete: science is not constructed solely within the outward-looking realm of social interaction. The individuals who participate in scientific work are not completely reducible to social networks. Scientists, as people, approach scientific problems with very personal beliefs, motivations, and tastes.[116] This sort of inward-looking analysis is equally necessary for an understanding of the scientific enterprise as considerations of research traditions and group dynamics. Niels Bohr and Albert Einstein were at once both individuals with particular motivations and goals, and interacting members of larger intellectual and social environments.

As a final reminder of the people behind the Einstein–Bohr debate, I close with an anecdote about the two physicists and their very human interactions:

> One morning Bohr came into [Abraham] Pais' office and with one of his ingratiating smiles began 'You are so wise.' Pais laughed (No solemnity ever was called for with Bohr, he noted). Bohr wanted Pais to come to his office to help him with a part of the answer to Einstein. Soon Bohr was furiously pacing around the oblong table in the center of the room. He would dictate a few sentences and Pais would take them down. 'It should be explained that at such sessions Bohr never had a full sentence ready,' said Pais. 'He would often dwell on one word, coax it, implore it, to find the continuation. This would go on for many minutes.'
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> This time Bohr halted at the word 'Einstein.' He was nearly running around the table, repeating 'Einstein... Einstein... Einstein...'
>
> At that instant the door opened softly and Einstein stuck his head in. As soon as he grasped the situation, he put his finger to his lips in a signal to Pais to say nothing, and to Pais' mystification tiptoed over to the central table. He was heading for Bohr's tobacco pot. Einstein's physician had forbidden him to buy tobacco, but had said nothing about borrowing some. At that instant, Bohr, with another firm 'Einstein,' turned around.
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> 'They were face to face as if Bohr had summoned him forth,' said Pais. For an instant Bohr stood there in frozen shock. He was speechless. Pais, who had realized what was coming but was helpless to stop it, had a sense of the uncanny. Only after a few minutes was the tableau broken. Then they burst into laughter.[117]

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[114] C. Rosenberg, 'Woods or trees? Ideas and actors in the history of science', *Isis* (1988), **79**, 567–8. Susan Krieger, a sociologist, has remarked that 'individuality is theoretically unpopular' in the social sciences as a whole, and argues for more explicit consideration to be paid to the researcher's individuality as well as to the individuality of the people studied. Like Rosenberg, she does not advocate study of the self to the exclusion of social and cultural contexts, but none the less encourages examination of aspects of individual personality and perspectives. S. Krieger, *Social Science* & *The Self*, New Brunswick, 1991, 43–5.

[115] Quoted in Heilbron, op. cit. (7), 143. Heilbron paraphrases Planck's view by writing: 'The final basis, the last authority, for the fundamental principles of physical science lie deep in the individual' (Heilbron, op. cit. (7), 143).

[116] A compelling historical portrait of this sort of fundamental person-hood is given by R. McCormmach, *Night Thoughts of a Classical Physicist*, Cambridge, Mass., 1982.

[117] Moore, op. cit. (4), 395. Cf. Pais, op. cit. (16), 12–13.