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Complementary Strategies in Scientific Discovery: Abduction and Preduction

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1. Introduction

Since the beginnings of the theory of knowledge nearly two and a half millennia ago, philosophers have tried different ways of reasoning in order to find out *the method of science*. This issue raised the question of whether this method should be unique for all the sciences, or whether each natural, social and human science should have its own method. Closely related to this discussion was the question – which I shall not address here – of the existence of a demarcation criterion between science and non-science.

After Peirce, deduction, induction and abduction were the primary ways of scientific reasoning employed by philosophers. This was until Hans Reichenbach pointed out that the whole issue of the methodology of science should to be analyzed from two different perspectives: that of the context of discovery and that of the context of justification. This distinction is of fundamental importance for the purpose of this paper.

Induction had traditionally been conceived of as a kind of truth conserving and content ampliative inferential form leading from the particular to the universal principles of science.[1] In the 20th century, Pierre Duhem and Albert Einstein, and later Karl Popper, began systematically to question

[1] In different forms, induction has persisted as *the method* of science for the twenty-four centuries in Western scientific thought since Aristotle: From the philosopher-scientists of the Oxford Franciscan School in the 13th century until John Stuart Mill in the 19th, taking in Francis Bacon and Isaac Newton, William Whewell and Herbert Spencer, among others. Especially important were inductive probability, developed as inductive logic by Rudolf Carnap in the fifties, and extended by Jaakko Hintikka in the sixties, as well as the contemporary Bayesian approaches to induction.

induction. Earlier, at the turn of the century, Charles Peirce proposed *abduction* as a complement to induction.

For Peirce, abduction was "the process of forming an explanatory hypothesis. It is the only logical operation which introduces any new idea; for induction does nothing but determine a value, and deduction merely evolves the necessary consequences of a pure hypothesis" (CP 5.171). This means that for him, both deduction and induction belong to the context of justification, whereas only abduction belongs to the context of discovery. Indeed, according to Peirce, induction "never can originate any idea whatever. No more can deduction", and "All the ideas of science come to it by the way of Abduction. Abduction consists in studying facts and devising a theory to explain them. Its only justification is that if we are ever to understand things at all, it must be in that way."

My concern is whether Peirce is right when he claims that deduction can never originate any idea whatever, so that all new ideas come exclusively to science by the way of abduction. My answer is that besides abduction, there is another form in scientific discovery, which I call *theoretical preduction*, or simply *preduction*. Indeed, *preduction* is the name I apply to the extension of the deductive way of reasoning to the context of scientific discovery. It consists in resorting to the available accepted results of theoretical physics as a whole, in order to make it possible to obtain, or to *anticipate*, new results by mathematical combination and manipulation, compatible with dimensional analysis, of the accepted results. Preduction is a form of *ars inveniendi* in theoretical physics.

I conceive both of them, abduction and preduction, as reasoning strategies in scientific discovery, abduction taking place, although not exclusively, in observational natural sciences, and preduction in the context of discovery of theoretical natural sciences. The distinction between observational and theoretical natural sciences is important from the viewpoint of the methodology of science. It points to the fact that in certain natural sciences the method of hypotheses testing is *not predominant*, but the method of guessing is. Since these natural sciences are basically grounded in observation, I call them observational sciences. Darwinism, palaeontology, and Earth sciences are paradigmatic examples. They rely on abduction as a reasoning strategy in scientific discovery, and lead to reasonable hypotheses about the available observational evidence, whereas the testing of the guessed hypothesis merely consists in a refinement of the procedures of collecting data, or simply in the comparison with novel data that contribute to increasing the available empirical basis. On the other hand, in theoretical natural mature sciences, such as mathematical physics, both the context of discovery and the context of justification are of an equal importance. In both, the hypothetical-deductive method is predominant: as hypothesis testing in the context of justification, and as *preduction* in the context of discovery.

The conclusion is twofold. First, the issue of *the* method of science reveals itself as a myth, since it is obvious that there is no one unique method. Secondly, as abduction and preduction complement each other – both of them nearly exhaust the whole work of creativity in the natural sciences – it is justifiable to claim a *complementarity thesis of abduction and preduction* in scientific discovery.

2. *Abduction* in philosophy and in science

That the place of abduction is the context of discovery becomes evident from Peirce's view that "Abduction is the process of forming an explanatory hypothesis. It is the only logical operation which introduces any new idea." Or "Abduction consists in studying facts and devising a theory to explain them." (CP 5.145; CP 5.171).

Although Peirce (CP 5.189), and later on Norwood Russell Hanson, in 1959, devised the logical form of abductive reasoning, the post-positivist philosophy of science in the last century, largely concerned with the problems of induction and inductive probability, widely ignored abduction. This was the case despite the fact that abduction has been thought of by Peirce as an inferential form in scientific discovery, and that Popper had claimed in the 1958 Preface to his *L.S.D.* that the central problem of epistemology is the growth of knowledge.

Nonetheless abduction had been enjoying a wide application in the natural sciences, as the following examples show:

- Ancient astronomy abduced hypotheses in order to account for planetary movements.
- One of the most celebrated abductions was Kepler's postulation of the elliptic character of Mars' orbit (CP 1.72–4; Hanson, 1958, pp. 84–85).
- A particularly interesting case of abduction, to be presented later here, is Alfred Wegener's (1880–1930) *continental drift hypothesis* proposed for the first time in his *Die Entstehung der Kontinente und Ozeane*, 1915.

- Darwin's evolutionary hypothesis in *On the Origin of Species by Means of Natural Selection*, 1859, was abductively postulated on the basis of the available biological and fossil data (This view is defended by Putnam, 1981, pp. 198–200).

- Ernest Rutherford's *atomic planetary model* was abductively postulated in 1911 on the basis of the alpha particles scattering experiments.

But it would not be fair to affirm that abduction has not attracted the interest of philosophers. In recent decades, the use of abduction has been identified in human activities such as medical diagnosis or criminal inquiry; this is evident in the contributions to *The Sign of Three* (Eco & Sebeok, 1983). But it is in artificial intelligence, logical programming, knowledge acquisition and related matters where abduction is being most-widely applied, as Josephson (1994), Magnani (2001; 2006), Flach and Kakas (2000), Aliseda (2006), and also Woods (2004), etc. show.

Moreover, following Harman's (1965) identification of abduction and *inference to the best explanation*, realist philosophers of science have assumed abduction as an argument for scientific realism. Richard Boyd, Peter Lipton, Ilkka Niiniluoto, Stathis Psillos, and Paul Thagard, among others, have contributed to this matter.

3. Abductive discovery in observational natural sciences

What was said in section 2, regarding the reception and acceptance of abduction, and especially the fact that abduction is still neglected in the methodology of science, may explain why philosophers of science have apparently not yet realized that observational natural sciences also constitute an outstanding empirical domain where 'explanation' is achieved almost exclusively by abduction. In this section I intend to fill in this gap.

Indeed, surprising facts, abduction by hypotheses elimination and selection of the most reasonable one, revision of abduced hypotheses by novel facts, etc., are phenomena currently occurring in observational natural sciences. Thus observational natural sciences still constitute an unexplored kingdom of abduction. They offer an excellent *milieu* for the philosophical investigation of scientific discovery. Let me illustrate this by reference to two successful, mature contemporary observational natural sciences: geology and palaeoanthropology.

The interest in the methodological aspects of geology/geophysics is widespread. Together with Robert Parker and Jason Morgan, Dan McKenzie (2001, p. 184) was one of the creators of the plate tectonics hypothesis between 1967 and 1968. He reflects this concern: "Few active scientists take much interest in general models of scientific discoveries, and I am no exception". Indeed, these scientists agree on: 1) the emphasis on the observational character of geophysics; 2) the conviction that the method of Earth sciences is not that of hypothesis testing; 3) the insistence that the context where geophysics develops itself is scientific discovery; 4) the use of terms such as "concept", "hypothesis", "pattern" to refer to what we can interpret as abduction; and 5) the extensive use of phrases like "the data could be explained if…", "this provided empirical evidence that…", "he proposed that … explaining that…", "his interpretation was confirmed by…", "he interpreted … as evidence in support of hypothesis…", "scientists now saw it as strong evidence of…", "he preferred to explain this phenomenon by…", "the observation could be interpreted simply with the model…", etc.

Indeed, according to McKenzie (2001, pp. 185–186), the fundamental difference between some branches of physics and Earth science lies in the fact that, whereas for the physical sciences, experimentation contributes to an essential part of the development of new theories, "hypothesis testing in its strict form is not an activity familiar to most earth scientists", and "I certainly would not describe Jason's and my activities in 1967 as hypothesis testing". And Sclater (2001, p. 137) confesses: "I have lost my belief that advances in the earth sciences occur primarily as a result of hypothesis testing. Neither Harry Hess nor Tuzo Wilson was testing a hypothesis". Sclater's view is that "Earth science is an observational discipline (…) Thus, unlike physics or chemistry, earth science is not an experimental discipline. Earth scientists, in most cases, observe and describe phenomena rather than conducting experiments to test hypotheses" (p. 138).

Nonetheless, observational sciences place their emphasis not only on guessing, but also on the rigorous foundation of empirical evidence. This means that hypothesis testing does also play a role in Earth sciences. Bearing in mind the hypotheses of sea floor spreading and plate tectonics, Sclater (op. cit., 144) claims that the process of discovery in the Earth sciences follows three steps: "The first involves the origination of the concept; the second, the construction of a model where the predictions can be compared with a set of observations, the third the application of the model to another set of data." This third step corresponds to hypothesis testing.

But contrary to the theoretical sciences, such as theoretical physics, where hypothesis testing occurs by experimental control of the mathematical consequences derived from the assumed hypotheses, in the observational natural sciences hypothesis testing can occur only by the discovery of new evidence that confirms or refutes the conjectured hypotheses. Seeking new data is the main control activity of abduced hypotheses. To proclaim that Earth sciences are observational sciences thus amounts to recognizing the relevance of the Peircean method of hypothesis in scientific discovery. But this is compatible with the assumption that discovery takes place over two steps: the first that of guessing, the second that of further empirical control.

3.1. Palaeoanthropology

Palaeoanthropology is a young science. Its origin dates back to 1856, when in a cave in Feldhofer, Neanderthal, near Düsseldorf, some hominid fossils were discovered. In 1861 they were identified as a different older species from modern humans: *Homo neanderthalensis*. Since then, interest in human evolution has developed in a spectacular fashion, following the discovery of more and older hominid fossils, with *Sahelanthropus tchadensis* close to being the common ancestor of hominids and chimpanzees.

From a methodological viewpoint, palaeoanthropology follows the procedure of a typical empirical science: surprising facts, hypothesis revision in the light of novel data, abduction by elimination of possibilities, the fallibility of hypotheses, new abduced hypotheses, and the beginning of a new cycle. Palaeoanthropologists are perfectly aware of this. Two examples suffice: in a paper on the comparison of the genomes of Neanderthals and modern humans, James Noonan et al. (2006) claim that "[o]ur knowledge of Neanderthals is based on a limited number of remains and artefacts from which we must make inferences about their biology, behavior, and relationship to ourselves." And Lorenzo (2005, p. 103) points out that "Philogenetic trees are only evolutionary hypotheses built upon a continuously changing empirical basis".

Contemporary palaeoanthropology allows us:

1. To recognize the existence of *surprising facts*. For instance, the discovery in 1978–1979, near the Serengeti National Park in Tanzania, of the *Laetoli footprints* left behind 3.6 million years ago by three biped *Australopitheci afarenses*, some Lucy's relatives. Or the discoveries between 1994–1995, in Sierra de Atapuerca, Burgos, Spain, leading to the abductive proposal of the new species *Homo antecessor*, whose

existence in Southern Europe drew back the presence of *Homo* from 500 000 years to 800 000 years BP.

2. To claim that the existence of all biped hominid genera like *Australopithecus*, *Paranthropus* and *Homo* was undoubtedly *inferred by abduction*.

3. To revise previously accepted hypotheses in the light of new data, for example the Laitman-Lieberman hypothesis, according to which Neandertals didn't speak. On the basis of the comparison of two Neandertal hyoid fossil bones already known with two hyoid bones from the middle Pleistocene, recently recovered in the Sierra de Atapuerca, Ignacio Martínez (2008) and the other members of the Atapuerca research group claim that both specimens "as well as the Neandertal hyoids, fall inside the modern human distribution, and all of the *Homo* fossils are clearly different from *A. afarensis* and the African apes."

4. To acknowledge the co-existence of *incompatible hypotheses* about the origin of our species: Franz Weidenreich's *multiregional hypothesis* vs. the *Out of Africa* hypothesis.

5. To accept that there are sometimes *insufficient available data for abductions*. For instance: there is insufficient evidence for the hypothesis that *Australopithecus garhi*, who lived 2.5 million years ago, preceded *Homo habilis* in the production of stone tools. Or there is insufficient available evidence for the inclusion of *Sahelanthropus tchadensis*, discovered in 2001, and *Ardipithecus ramidus*, discovered in the 1990s, in the family of biped hominids.

3.2. Earth sciences

3.2.1. *The continental drift* hypothesis

The empirical basis of the reasoning that led Alfred Lothar Wegener (1880–1930) to the *continental drift* hypothesis consisted of an enormous amount of observational data of different character:

1. *Geodetic data*: Observation, on the basis of astronomical, radiotelegraphic and radio-emission measures, of the continuous separation of Europe and America.

2. *Geophysical data*: Agreement of the Fennoscandian rebound with the isostasy hypothesis.

3. *Geological data*: Affinities between the plateaus of Brazil and Africa, and between the mountains of Buenos Aires and the Cape region, etc.

4. *Palaeontological data*: The distribution of the Glossopteris flora in Australia, South India, Central Africa and Patagonia, and of Mesosaurus in Africa and South America

5. *Palaeoclimatical data*: In *Pangea*, the Poles did not coincide with the current ones. Tropical and subtropical regions today were covered with ice 300 million years ago, whereas the Spitzberg Islands, nowadays affected by a polar climate, enjoyed a much warmer climate in the Mesozoic and in the Palaeozoic.

Wegener (1966, p. 167) himself recognizes that "The determination and proof of relative continental displacements ... have proceed purely empirically, that is, by means of the totality of geodetic, geophysical, geological, biological and palaeoclimatic data ... This is the inductive method, one which the natural sciences are forced to employ in the vast majority of cases." These data suggested both the hypothesis that the continents had built a super-continent, *Pangea*, in earlier times, as well as the continental drift hypothesis.

3.2.2. The *plate tectonics* model

Continental drift is not the whole truth. What causes it? How can it be explained? Since 1968 the answer has been: the plate tectonics dynamics, according to which the lithosphere consists of plates moving above an astenosphere formed of plastic materials.

Even the hypothesis of the dynamic of plate tectonics can be *abduced* itself on the basis of much new data that came to support the continental drift theory during the period 1955–1968:

1. The discovery in 1959 of the mid-ocean ridge with a rift valley, or medial rift, running along the crests of the ridges, and Harry Hess's (1906–1969) and Robert Dietz's (1914–1995) *sea floor spreading* hypothesis.

2. Motonari Matuyama's 1920s discovery of the Earth's magnetic field reversion in the Pleistocene (some 10 000 years ago), and the establishment of a chronology of the epochs of normal and inverse polarity.

3. Jim Heirtzler's discovery of the 'magic' magnetic anomaly profile, obtained over the 600-mile South Pacific ridge crest, that led to the confirmation of the *Vine-Matthews hypothesis*: "if the sea floor spreads while Earth's magnetic field reverses, then the basalts forming the ocean floor will record these events in the form of a series of parallel 'stripes' of normal and reversely magnetized rocks" (Oreskes, 2001, pp. 22–23).

Based on these discoveries, Daniel McKenzie, Robert Parker and Jason Morgan established in 1967–1968 the *plate tectonics model*: "crustal motions could be understood as rigid body rotations on a sphere". This model was completed by Le Pichon (2001, p. 216): "*a unique solution could only be obtained* by using six plates … This six-plate model accounted for most of the world's seismicity, as Bryan Isacks and his colleagues would later show."

4. Preduction in the context of discovery of *theoretical* natural sciences

For the sake of the argument, I start with Peirce's view that deduction can never originate any idea whatever. I disagree with Peirce that all "the ideas of science come to it by the way of Abduction" (CP 5.145). Thus my main aim during the rest of this paper is to answer to the question: *Can deductive reasoning be used in the context of scientific discovery?* My thesis is that it can.

If I am right, then the alleged *weakness* of the hypothetical-deductive method, which Medawar (1974, p. 289) pointed to – "The weakness of the hypothetic-deductive system, …, lies in its disclaiming any power to explain how hypotheses come into being" – would be overcome. In opposition to Medawar, I affirm that *in theoretical physics* we can extend the application of deductive reasoning to the context of discovery. Thus a new form of reasoning, preduction, becomes acceptable. This confirms Thomas Nickles's (2008, p. 446) suspicion that "even an ordinary deductive argument need not be sterile: it may be epistemologically ampliative even though it is not logically ampliative". But because of its deductive nature I prefer to conceive of preduction as an *anticipative* inference. *Anticipative inference* is not a logical concept. It merely points out that preduction deductively anticipates or puts forward some not yet acknowledged possible empirical and theoretical results.

Preduction is the way of reasoning that consists in resorting to previously accepted results *of the whole of physics*, in order to anticipate new ideas by mathematical combination and manipulation of the used results, provided that the undertaken substitutions and combinations are compatible with *dimensional analysis*. This is on the understanding that 'previously accepted results' does not mean 'accepted as true'.

A very simple example is Einstein's theoretical deduction, i.e. *preduction*, of the dual character of photons by *combination of two previous results of different theories*, special relativity and Planck's quantum physics. Indeed, from $E = cp$ (*special relativity*), and $E = h\nu$ (quantum physics), we obtain the result $p = h/\lambda$, or $\lambda = h/p$, i.e. the formulas expressing the dual behaviour of radiation.

Two more examples may be sufficient to illustrate the preductive way of reasoning in mathematical physics.

A. The critical density of the Universe.

1. Let us assume a symmetrically spherical Universe of radius R and mass $M = (4\pi R^3\rho)/3$.

2. Let us assume now a galaxy of mass m located on the surface of the Universe. Its *Newtonian* potential energy is $E_p = -(G_N Mm)/R$, and its kinetic energy is $E_c = mv^2/2$.

3. Let us now take *Hubble's law* from *astrophysics*, which applied to present situation has the form $v = H.R$. Following this, the galaxy's kinetic energy would be $E_c = mH^2R^2/2$.

4. Thus the total energy of the galaxy, substituting the value of M in 1., becomes $E_T = mR^2(H^2/2 - 4\pi G_N\rho/3)$.

5. Now, if $E_T = 0$, then $H^2/2 = 4\pi G_N\rho/3$, whereof we obtain the value of the *critical density of the Universe*: $\rho_c = 3H^2/8\pi G_N$.

B. Schrödinger's equation

1 We start with wave theory, where a non-relativistic free particle has associated a plane wave:
$\Psi(x,t) = A_e{}^{i(kx-\omega t)} = A[\cos(kx-\omega t) + i\,\sin(kx-\omega t)]$

2.1 Then we differentiate this expression with respect to x, and apply De Broglie's postulate of *quantum physics* $\lambda = h/p$ to the wave number $k = 2\pi/\lambda$ in order to obtain $k = p/\hbar$, and finally the *momentum operator* $-i\hbar\partial/\partial x$.

2.2 We now differentiate the same expression with respect to t. Then we divide $\omega = 2\pi\nu$ by the wave number $k = 2\pi/\lambda$, and apply Planck's *quantum hypothesis* $E = h\nu$, in order to obtain $\omega = Ek/p$, and finally the *energy operator* $i\hbar\partial/\partial t$.

3 We resort now to the *classical* equation of the total energy of a non-relativistic particle as the sum of its kinetic and potential energies: $E = p^2/2m + V$.

4 Finally, we insert the values of momentum and energy operators, and obtain *Schrödinger*'s equation:
$-\hbar^2/2m.\partial^2\Psi(x,t)/\partial x^2 + V(x,t)\Psi(x,t) = i\hbar.\partial\Psi(x,t)/\partial t.$

As the above examples show, the following are the main features of preduction:

- Preduction is the way by which new factual hypotheses, theoretical laws and theoretical models can be postulated in physics by combination, compatible with dimensional analysis, of previously accepted results.

- Preduction starts with previously accepted results of the whole theoretical background that are postulated *methodologically* as premises of the inferential procedure. Since these premises have only a hypothetical character, *accepted* does not imply *accepted as true*.

- As the premises of preductive inferences are accepted results proceeding from different theories, preduction is transverse or inter-theoretical deduction. This is what makes it possible to introduce new ideas in physics.

- To preduce a new theoretical model or a novel hypothesis amounts to deductive-mathematically generating an equation or a set of coupled equations, whose consequences should fit with observations.

- Preduction is an implementation of the hypothetic-deductive method. The *specificity of preduction* lies in that it is an extension of this method to the context of discovery.

5. Some conclusions on the relationships of abduction and preduction

Preductive reasoning differs radically from abduction in that the preduced hypotheses are not suggested by the data, but they are instead deductively obtained from the available theoretical background. Abduction and preduction complement each other. Whereas abduction is the way of reasoning in observational sciences, preduction is the predominant, although not exclusive, form of discovery in theoretical sciences. Thus both ways of reasoning nearly cover the whole spectrum of discovery in the methodology of natural sciences. I call this the *complementary thesis between abduction and preduction*.

Abductive and preductive inferences are both intrinsically inconclusive. Indeed, in the case of abduction, new facts might emerge to the detriment of the conjectured explanations, thus making it reasonable to revise or even to replace them by new ones, compatible with the old and the new data. In the case of preduction, since the hypotheses, theoretical models and other preduced results depend on the available theoretical background, and since it is assumed that this one can be not true, preduction itself also becomes a fallible way of reasoning as a way of dealing with Nature.

Rather than talking about *the* method of science, I claim that it would better fit with the procedure of real science to take into account the existence of different practices or strategies in scientific discovery.[2]

References

Aliseda, A. (2006). *Abductive Reasoning. Logical Investigations into Discovery and Explanation*. Dordrecht: Springer.

Eco, U., & Sebeok, T. A. (Eds.) (1983). *The Sign of Three. Dupin, Holmes, Peirce.* Bloomington: Indiana University Press.

Flach, P. A., & Kakas, A. C. (Eds.) (2000). *Abduction and Induction. Essays on their Relation and Integration*. Dordrecht: Kluwer.

Hanson, N. R. (1958). *Patterns of Discovery. An Inquiry into the Conceptual Foundations of Science*. Cambridge: University Press.

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Harman, G. H. (1965). "The Inference to the Best Explanation." *The Philosophical Review*, 74(1), 88–95.

Josephson, J. R., & Josephson, S. G. (Eds.) (1994). *Abductive Inference. Computation, Philosophy, Technology*. New York: Cambridge University Press.

Le Pichon, X. (2001). "My Conversion to Plate Tectonics." In N. Orestes (Ed.), *Plate Tectonics*. Boulder: Westview Press.

Lorenzo, C. (2005). "Primeros homínidos. Géneros y especies." In E. Carbonell (Ed.), *Homínidos: Las primeras ocupaciones de los continentes.* Barcelona: Ariel.

Magnani, L. (2001). *Abduction, Reason and Science. Processes of Discovery and Explanation.* New York: Kluwer/Plenum Publishers.

Magnani, L. (Ed.) (2006). *Model Based Reasoning in Science and Engineering.* London: College Publications.

Martínez, I. et al. (2008). *Human Hyoid Bones from the Middle Pleistocene Site of the Sima de los Huesos* (Sierra de Atapuerca, Spain). *J. Hum. Evol.* 54(1), 118–124.

McKenzie, D. (2001). "Plate Tectonics: A Surprising Way to Start a Scientific Career." In N. Oreskes (Ed.), *Plate Tectonics.* Boulder: Westview Press.

Medawar, P. (1974). "Hypotheses and Imagination." In A. Schilpp (Ed.), *The Philosophy of Karl Popper.* La Salle: Open Court.

Nickles, T. (2008). "Scientific Discovery." In Psillos, S. & Curd, M. (Eds.), *The Routledge Companion to Philosophy of Science.* London: Routledge.

Noonan, J. P. et al. (2006). "Sequencing and Analysis of Neanderthal Genomic DNA." *Science*, 314, 1113–1118.

Oreskes, N. (2001). "From Continental Drift to Plate Tectonics." In N. Oreskes (Ed.), *Plate Tectonics.* Boulder: Westview Press.

Putnam, H. (1981). *Reason, Truth and History.* Cambridge: University Press.

Sclater, J. G. (2001). "Heat Flow under the Oceans." In N. Oreskes (Ed.), *Plate Tectonics*. Boulder: Westview Press.

Wegener, A. L. (1966). *The Origin of Continents and Oceans.* New York: Dover.

Woods, J. (2004). *The Death of Argument. Fallacies in Agent Based Reasoning.* Dordrecht: Kluwer.