Chapter 16
The Causal Strength of Scientific Advances

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16.1 Units of Scientific Knowledge: Advances

The project of developing a science of science that takes as empirical data the vast work of historians of science, and that takes as theory (or "metatheory") the ingenious accounts of scientific development proposed by philosophers, stumbled on the difficulty of testing the different metatheories (the attempt that went the farthest in this direction was that of Donovan et al., 1988). One possible solution would be to use computers to store the historical information and run programs that could test different metatheoretical theses. But how should the historical information be represented in computer language?

A simple approach is to read the narrative of any historian of science and represent its salient aspects. As an example, consider an excerpt by Daniel Siegel referring to the nineteenth century field of spectroscopy, which is part of the general case study being used to develop our computer model (see footnote[1]). The author writes about certain *problems*, which stimulated the construction of an *instrument*, which was important for the confirmation of a *hypothesis* (that the bright spectroscopic D lines are due to sodium), which in turn was important for the *discoveries* of Robert Bunsen and Gustav Kirchhoff. The historian writes about problems, instruments, discoveries, ideas, theories, laws, etc., and each of these

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[1] "The resolution of these problems was greatly facilitated when Robert Bunsen, in the mid-1850s, introduced a lamp which provided a hot flame of low intrinsic luminosity; with the 'Bunsen burner' flame spectra could be observed against a minimum of disturbing background, and spectrum analysis was thereby facilitated in general. In particular, William Swan, using the Bunsen burner, was able to show convincingly in 1856 that the bright D lines could be attributed to sodium, the ubiquity of the D lines being due to general contamination with small amounts of that element. It was against this background that Bunsen and Kirchhoff undertook their collaborative researches of 1859–1860" (Siegel, 1976, pp. 568–9).

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have an influence, in differing degrees, on the appearance and confirmation of other scientific advances.

Let us then single out such "units of scientific knowledge" (ideas, instruments, etc.) and represent each of them in our information basis. Various names have been given to such units (contributions, achievements, manifestations, novelties, cognitive memes), but for brevity we shall call them "advances", even though they might not be a positive contribution to the progress of science. An advance is any scientific knowledge that is explicitly or tacitly passed among scientists. The prototype of an advance is an idea, but there are other types of theoretical advances, such as explanations, laws, problems, theory development, as well as experimental advances, such as data, experiments, and instruments. Other advances include the comparison between theory and experiment, methodological theses, metaphysical assertions, projects, tacit knowledge, etc.

Advances are part of what is usually called "internalist" history of science. The so-called "externalist" conditions (psychological, social, economic factors) are also important for explaining scientific development, but are not included in the definition of advance. The distinction between advances and cultural manifestations is however not always clear-cut, and it is sometimes useful to include the latter as a type of advance, especially when examining the origins of science (Pessoa, 2005).

Also excluded from the definition of advance are the facts in nature (described by the natural sciences). For example, in the context summarized in Siegel's quotation, there was a problem of contamination of all samples, notably by sodium, which made it difficult to identify the spectral lines characterizing each substance. Before there was a general recognition of this fact, around 1856, there was no corresponding advance (which may be called the "problem of spectral background"), even though the fact played a causal role in the development of spectroscopical science.

16.2 Probabilistic Causal Relations Between Advances

A second feature of the historian's discourse is that the advances are connected in certain ways, they influence the *appearance* of other advances, and they also affect the *degree of acceptance* of other advances. In the present approach, such a connection is taken to be a *causal* relation, not a logical one. For example, the construction of the Bunsen burner was essential for William Swan's discovery that the bright D lines are sodium: without the Bunsen burner, Swan would not have confirmed that debated hypothesis. The Bunsen burner may therefore be considered a "cause" of Swan's discovery, in the sense expressed by the so-called counterfactual definition of causality. This definition was given in an isolated passage by David Hume (1748, Section VII, § 29), for the case of a necessary condition: "Or in other words, *where, if the first object had not been, the second never had existed*".

When a scientist derives a new theoretical result, such a result is usually presented as a logical inference based on other advances. Although the connection between these advances is presented as a logical relation, a consideration of the actual circumstances of the derivation will point out which of the advances are the causes (being previously known), and which one is the effect (the new result). When a scientist justifies a result in deductive form, there are at least two possibilities for the causal history of the result: either the premisses are the actual causes of the conclusion (so the scientist actually discovered the conclusion by deductive inference from the premisses), or the conclusion was previously accepted by the scientist and led him to formulate a premiss as an explanatory hypothesis, in an abductive inference. The present approach sees a scientist as a very complex cognitive machine that receives a large number of advances (with changing degrees of acceptance) as causal inputs and generates new advances, which will causally affect himself and other scientists.

Causal relations in social systems are always complicated, and one can rarely single out a necessary and sufficient condition. A cause is better represented as an "INUS condition" (Mackie, 1965), which amounts to saying, in the example quoted from Siegel, that many other causes acted together with the Bunsen burner to lead Swan to his discovery, and that probably another sufficient set of conditions (not including the Bunsen burner) could have led to his discovery.

Another weakening of these causal relations is that a set of conditions can at best increase the *probability* that a scientist will arrive at a certain advance in a certain interval of time. The great number of causal influences that act haphazardly on a scientist, but cannot be accounted for by the model, are considered as "noise" or random fluctuations, the dispersion of which is encompassed by the probability functions.

16.3 The Representation of Causal Connections

How should causal connections and their strengths be encoded in computer language? We will consider another simple example and work with a visual representation of advances as blocks, and of causal connections as arrows.

In 1672, Isaac Newton announced the results of his experiments with sunlight and prisms, which would have a large influence in subsequent research. One of the discoveries that would be later made with his basic experimental setup was the identification of dark lines in the solar spectrum, by William Wollaston, in 1802. Wollaston was interested in the problem of how many colors there are in the solar spectrum, and so he passed sunlight through a long slit (Newton had used such slits, but preferred a round orifice) and through a flint glass prism, and with his unaided eye observed, to his surprise, the presence of seven dark lines, some of which seemed to separate what he took to be the sun's four basic colors.

This simplified causal relation is represented in Fig. 16.1, where other causal factors are ignored.

Assuming that the figure adequately represents the historical relations between the two advances, one question concerns the "strength" of the causal relation: how

Fig. 16.1 Simple causal relation between two advances

should it be numerically represented in a computer program? An initial consideration is that the time interval between the appearance of the first advance and of the second is an indication of this strength: the shorter the time, the stronger the cause. This suggestion has been examined in more detail in Pessoa (2006), where an ensemble of possible histories of science is considered, and a probability distribution function is associated to each causal relation. Such a function expresses the distribution of times between the two advances, in the set of possible worlds, and the restriction is imposed that the time average is equal to the actual number of years between the appearances of the two advances (in the present example, 130 years).

One may evaluate the causal strength more precisely in the case of independent discoveries. In 1814, without being aware of Wollaston's observation, Joseph von Fraunhofer rediscovered the dark lines in the sun's spectrum, while investigating the problem of dispersion of light in different types of glasses. He also used a long slit but had a superior equipment, using an achromatic refracting telescope to view the spectrum and Pierre Guinand's high quality glass for the optical instruments.

With two independent discoveries, one may estimate not only the time average of the aforementioned probability distribution, but also its dispersion (standard deviation). Composition of causes (A causes B, and B causes C) may be readily represented by summing the time averages ($t_{AC} = t_{AB} + t_{BC}$) and by summing the squares of the dispersions ($\delta_{AC}{}^2 = \delta_{AB}{}^2 + \delta_{BC}{}^2$) (Pessoa, 2009b). The upshot of this discussion is that the actual time interval (called "empirical time") between two advances linked by a causal relation is a first measure of the strength of the causal connection, and should be included in the computational representation of advances. With the actual empirical time between two causally linked advances A and B, one can estimate the probability (for possible worlds), after the occurrence of A, that the effect B will appear in a certain time interval ΔT.

Figure 16.2 represents the two actual paths leading to the independent discoveries of dark lines in the solar spectrum. Both were influenced by Newton's experiments, and both employed a long slit and a flint glass prism. The discovery was unexpected,

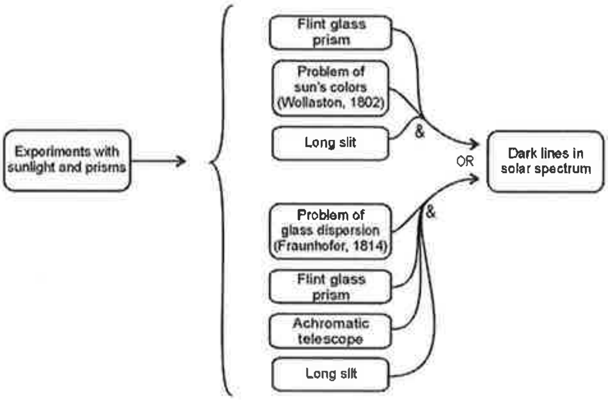

Fig. 16.2 Two actual paths leading to the same advance

and the problems which motivated the experiments were different in each case. In addition, Fraunhofer used a superior equipment, including the achromatic telescope. The causal diagram exemplifies the aforementioned "INUS condition" (weakened to probabilistic causal relations), where either of two sets of sufficient conditions (each of them constituted by a conjunction "&" of necessary conditions) may give rise to the effect.

Independent discoveries are especially interesting for building causal models in the history of science, since they correspond to two possible paths that are actual (not counterfactual). "Almost discoveries" are also of interest, such as the case of Thomas Melvill, who pioneered chemical analysis with flames in 1752, but died the following year at the age of 27. The historian Harry Woolf (1964, p. 628) remarked that Melvill "was clearly on the road to major discovery in science", which would include the discovery of the dark lines in the solar spectrum. Such an advance could therefore have appeared around 1760, in a counterfactual scenario.

When working with causal models, one may choose to include similar counterfactual information or not. It is highly probable that if Melvill hadn't died, he would have arrived at the advance, but one problem with including this "if hadn't died" information in our data base is that one could equally well include "if had died" information. In our example, it could also have happened that the young Fraunhofer died when the glass-making workshop where he worked collapsed in 1801. If one wants to maintain our actual history as the mean of the set of possible worlds being considered (which statistically should be our best guess), then counterfactual scenarios should be introduced in balancing pairs (such as the aforementioned "if had died" and "if hadn't died" pair) (this was *not* done in Pessoa, 2009b).

16.4 Causal Strength of an Advance

The time taken between the appearances of two advances that are causally linked is an indicator of the strength of the cause in producing the specific effect. But the more interesting aspect of such a concept of "causal strength" is that it is measure of the degree of acceptance of the advance, and it varies with time, as scientists discuss its merits. If the advance is an idea, this discussion might involve debating its degree of confirmation, which affects the degree of acceptance of the idea. If the advance is a new instrument, different scientists must investigate its performance, which then affects how trustworthy are its measurements. If the advance is a problem, then its strength reflects how many scientists are concerned with it.

The *causal strength*[2] of an advance may be defined as the potentiality that it may influence the appearance of other advances, or that it may affect the causal strength of other advances (mediated, of course, by the brains and hands of scientists, and by their social and institutional interactions).

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[2] The term "causal power" could be used, but it seems to be committed to a realist conception of causes, which I would like to avoid in the present exploratory stage of the project.

A theoretical advance may start out as a simple consideration of an idea, then develop into the proposal of a hypothesis, then be explicitly defended, then it may be considered plausible, and then acquire good evidence, then strong support, and finally wide acceptance. These may be called "degrees of acceptance" of a hypothesis, and the causal strength of an idea grows as its acceptance grows. A hypothesis may also receive negative support, in varying degrees, and this has an effect on its causal strength (which may be nullified, or may cause the downfall of other advances).

Similar considerations may be applied to an experimental advance, such as an instrument. An instrument might be built based on a new principle, but at first its performance might be bad, then its resolution (or other figure of merit) might improve, leading to increasing use of the instrument. The notion of causal strength (the capacity of an advance to give rise to new advances) still applies here. But for instruments, the causal strength is not only dependent on the degree with which it is used or sold (analogous to an idea's degree of acceptance), but also on its figures of merit: a higher resolution allows more precise data, which increase the possibility of discovering new advances (such as new phenomena or laws).

Let us consider the historical example of an explanation (a theoretical advance), the thesis that the dark lines in the solar spectrum originate in the sun's atmosphere. It was first suggested around 1832 by John Herschel and David Brewster, and we may attribute to it a causal strength of 0.3 (out of a maximum value of 1.0). It stimulated further research, and 2 years later Brewster obtained data from the sun that seemed to confirm the hypothesis, so its strength rose to around 0.6. But then, during the eclipse of 1836, James Forbes observed no differences while looking at the spectrum of the sun's corona, and concluded that the dark Fraunhofer lines do *not* arise in the sun's atmosphere. We may thus lower the causal strength of the hypothesis to 0.1, since it was rejected by most spectroscopists, but still attracted attention. Brewster himself, as late as 1859, with J.H. Gladstone, reconfirmed Forbes' negative conclusion. But in that same year, Kirchhoff showed convincingly that the dark lines of the solar spectrum are not caused by the earth's atmosphere, but originate from the presence of chemical elements in the glowing solar atmosphere (McGucken, 1969, pp. 15–33). So now the causal strength rose to around 0.9 (later, it was found that some lines are in fact generated in the earth's atmosphere).

Although the numerical measure for the causal strength is only a rough estimate, it is useful as an input for computations. One should also consider that different scientists or research programs might have different degrees of acceptance for an idea. In the example just given, coming from another field in 1854, William Thomson considered quite plausible the hypothesis that the dark lines originate in the solar atmosphere.

16.5 The Representation of Causal Strengths

We have argued above, when working with causal models in the history of science, that an advance should always be considered together with an estimate of its causal

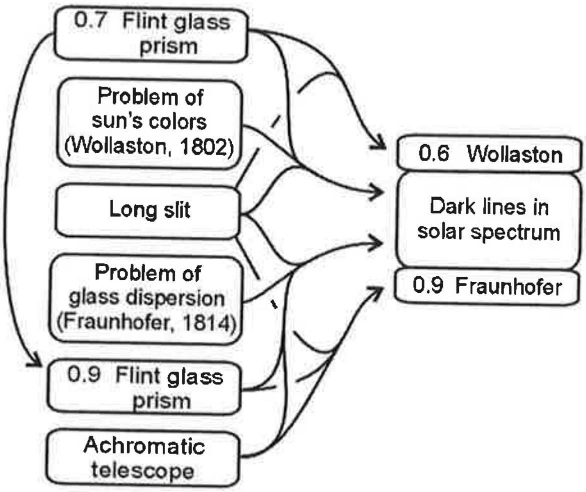

Fig. 16.3 Two paths leading to different causal strengths of the same advance

strength, which usually varies with time. Figure 16.3 is a version of the example given in Fig. 16.2, in which measures of the causal strength are tagged on to two different advances, "flint glass prism" and "dark lines in solar spectrum". All of the causal connections for the *appearance* of the effect in Fig. 16.2 are reproduced in Fig. 16.3; but, in addition, new arrows are drawn pointing to the different *causal strengths* of the effect "dark lines in solar spectrum".

We have seen that Fraunhofer worked with a higher quality prism, so we might represent this higher quality by stipulating that its causal strength is 0.9, instead of the lower quality of Wollaston's prism, which we might fix at 0.7 (One could consider that the two different prisms correspond to two different advances, but for our purposes it is simpler to consider them as the same advance, with different causal strengths).

Consider now the resulting advance discovered by the two scientists, the dark lines in the solar spectrum. Wollaston's discovery did not attract the attention of other scientists, in part because at that time it was still a subtle effect, not so easily reproducible, so we might attribute to his finding a degree of acceptance of 0.6, as represented in Fig. 16.3. Fraunhofer's data, on the other hand, had much higher accuracy, and he was able to map hundreds of lines. His result was unquestionable, so we attribute to his proposal of the advance a degree of acceptance of 0.9.

Our ground rule, before the explicit consideration of causal strengths, has been that "the *appearance* of an advance is causally influenced (in a probabilistic way) by the *presence* of other advances" (rule 1). With causal strengths, one notices that "the *appearance* of an advance is also causally influenced *by the causal strengths* of other advances" (rule 2). Furthermore, "the *causal strength* of an advance is causally influenced by the *presence* of other advances" (rule 3), which may lend support to it.

Let us now return to the causal strengths of the previous advance "flint glass prism". One could argue that it is the lower causal strength of this advance that led to a lower degree of acceptance of the effect "dark lines in solar spectrum". Identifying the latter's degree of acceptance with its causal strength, one may take this to be an example of a general rule (with possible exceptions) for causal models in the history of science: the causal strengths of the effects vary monotonically with the causal strengths of the causes. In other words, "the *causal strength* of an advance is also causally influenced by the *causal strengths* of other advances" (rule 4). Included in these rules is the obvious statement, indicated in Fig. 16.3 by the vertical arrow between the two versions of "flint glass prism", that a new degree of causal strength is causally influenced by the previous degree of the *same* advance.

We have focused on the prisms in order to explore the notion of causal strength, but the greater resolution and accuracy that Fraunhofer had over Wollaston was due to other instruments, especially the achromatic telescope for looking at the spectrum. The Bavarian scientist also used a theodolite for making precise angular measurements. So all of these advances contributed causally for the appearance of the effect, and most of them contributed to its degree of acceptance (and causal strength).

On the other hand, we notice in the figure that Wollaston's advance "problem of sun's colors" and Fraunhofer's "problem of glass dispersion" do *not* contribute to the degree of acceptance of the effect. These two advances were important for making the scientists explore the field (in the context of discovery), but once the discovery was made, these advances became irrelevant for the context of justification, which is involved in the degree of acceptance.

All of these considerations are represented in the diagram of Fig. 16.3, with is a rather complicated network for the simple appearance of an advance by two independent paths. Causal models become quite complicated once causal strengths (degrees of acceptance, qualities of instrument, etc.) are represented, but this complication may be stored in the computer, out of our sights.

16.6 Outlook

The present paper is part of an ongoing project of representing the beginnings of quantum physics by means of causal models in the history of science, with the aid of computers. In a preliminary study of the possible paths leading to the birth of the old quantum theory (Pessoa, 2001), it was suggested that there would be four main paths, the most probable not being the actual one (in the field of thermal radiation), but in the field of optical effects. A simple causal model helped to organize the study, but the conclusion was reached "intuitively", and should be qualified and refined with a more detailed causal model.

Computer programs don't provide actual thinking and intuition, but they allow the storage of detailed information concerning the relations between advances and their causal strengths, and allow simulations to be run, which we hope might help to test metatheoretical theses about the development of science. There are many different types of advances, and the general relations between these types may be investigated with the aid of the computer. One may also imagine attempts to represent (Pessoa, 2009a) and generate counterfactual histories of science (which should however be very "close" to actual history, so that most advances can maintain their identity across possible histories, and basically the order of their appearances is changed), in spite of the controversy surrounding the subject of counterfactuals (see Radick et al., 2008).

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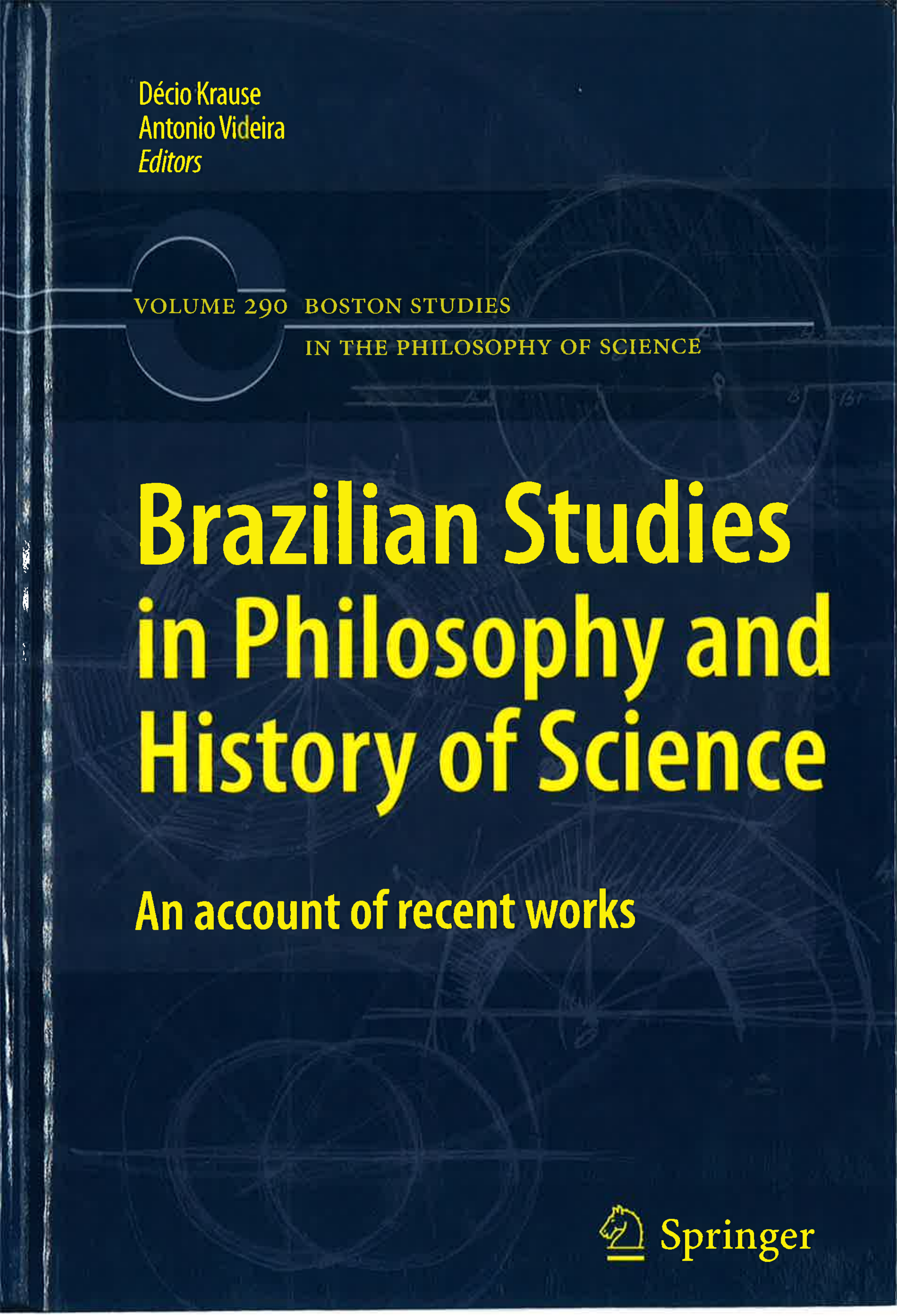

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