# Counterfactual Histories: The Beginning of Quantum Physics

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This paper presents a method for investigating counterfactual histories of science. A central notion to our theory of science are "advances" (ideas, data, etc.), which are units passed among scientists and which would be conserved in passing from one possible history to another. Advances are connected to each other by nets of causal influence, and we distinguish strong and weak influences. Around sixty types of advances are grouped into ten classes. As our case study, we examine the beginning of the Old Quantum Theory, using a computer to store and process historical information. We describe four plausible possible histories, along with six other implausible ones.

**1. Introduction.** Most everyone agrees that the history of science could have been different, since so many fortuitous factors affect the development of any area of science. This being so, what other histories of science could have been possible?

The historian usually turns away from this sort of question, since there isn't a direct way of investigating "counterfactual" histories, that is, possible histories that did not occur. Some historians have devoted themselves to this type of "imaginary history," but the consensus in the field, as stressed by E. H. Carr, is that such "parlor-games with might-have-beens," in spite of being logically correct, are not the mode of discourse of History (see Hawthorn 1991, 1–9).

However, the history of science (more so than the histories of other fields) presents a strong restriction in its development (Hund 1966, 23): scientists of the past worked in search of "objective" phenomena, laws, and theories now known to us but (up to a certain time) unknown to them. With the advantage of hindsight, we are capable of evaluating how far different scientists were from the discovery of a new principle, and, there-

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fore, of evaluating what could have happened if a fortuitous event had prevented a scientist from discovering a new principle.

Before attacking the problem of how to construct plausible counterfactual histories, let us examine what would be the advantage of doing this. Why counterfactual histories? The main motivation is to contribute to the field of "theories of scientific change," which had its high point in the 60's and 70's with the debates involving Kuhn, Lakatos, Laudan, etc. (Laudan et al. 1986). This may be seen as an attempt at making a "science of science." If the intention is to build a science of the development of science, then the notion of *cause* must be central (as it is in any branch of science).

Now, in any science, the notion of a "cause" that precedes an effect implicitly carries an indication of the possibility that would actualize (that is, of the state of things that would occur) had the cause not taken place. If we say that the cause of a rock's heating is the presence of the sun, implicitly we are saying that in the absence of the sun the rock would remain cold. Any assertion about a cause can be translated to an assertion about counterfactuals (see the discussion in Lewis 1973). Analogously, the notion of a cause in the historical sciences can only have an explicative function if one has an idea of the possible histories that did not happen. If the counterfactual histories of science could be mapped, one could explain in a better way *why* the different episodes in the history of science occurred.

**2. Counterfactual Histories of Quantum Physics.** The case study chosen is the beginning of the Old Quantum Theory in the second half of the 19th century. The first great discovery leading to Quantum Mechanics was that of energy quantization by Max Planck in December 1900. Some authors believe that the path taken to this discovery, in the field of Thermal Radiation, was quite "improbable," having depended on the brilliance of various scientists. According to this opinion, if Planck had chosen another profession, most probably Quantum Physics would have begun in a field different from that of Thermal Radiation.

An author who has written about the possible histories of Quantum Physics is the physicist and historian Friedrich Hund (1966), who worked in spectroscopy in the 1920's. In a short article, he sketched various possible paths leading to different stages in the development of Quantum Theory. In spite of the many suggestions that he offers of counterfactual historical paths, his work is not systematic and does not encompass all the range of research done at the time, especially the experimental work.

What we attempt to do in this work is to analyze in more detail the history of science of the period, in order to postulate different counterfactual histories and to place such speculations on firmer and more detailed grounds. We believe that *computation* has an essential role in concatenating more precisely the abundance of historical data with the predictions of the theories of scientific change. In the present project, we have used the language SCHEME to store historical information (from papers published between 1800 and 1915) and to run programs which extract relevant information for the mapping of counterfactual histories.

At this initial stage of our work, we have restricted ourselves to information obtained from secondary literature, especially from the books by Jammer (1966), Mehra and Rechenberg (1982), and Brush (1976). This imposes certain limitations, but our main concern at this stage is: (i) to establish an adequate methodology for studying counterfactual histories; (ii) to store the historical information and to write computer programs that can do research using the database; and (iii) to study the conceptual novelties that might appear from the present methodology, such as the notion of "advance," the classes of types of advances, and the types of causal influence.

In Section 7 we present our preliminary conclusions concerning the counterfactual histories of Quantum Physics, which are limited by a lack of information about the development of experimental techniques. This information is important for the assessment of how soon the empirical discoveries involved in the different possible histories could have been made. We intend to correct this limitation in the continuation of the project—the examination of the primary sources—in order to obtain more detailed results, faithful to historical events. It should be stressed that various authors have been doing detailed historical-philosophical studies on the development of traditions in *experimental* science (more recently, we might mention Holton et al. 1996, and Hentschel 1997, which presents further bibliography).

**3. Advances and Their Network of Influences.** When writing scientific papers, scientists usually refer to the pertinent influences they received by means of citations. These influences may be considered "causal," since they involve events in the real world and the (counterfactual) absence of one of them would result in a different paper (or even in the nonexistence of the paper, for strong causal influences). It is possible to connect the different articles of a period by means of these causal influences, establishing a *network of influences between articles*.

However, since we are interested in postulating counterfactual histories, it is not very relevant to establish which article influenced which other. What is important for us are the ideas, the experimental data, and other "advances" contained in the articles, which we will suppose would also be present (to a large extent) in counterfactual histories (while the articles and scientists involved could vary from one history to another). Therefore, the fundamental aspect of the method is to establish a *network of causal influences between "advances."* Figure 1 presents a network of influences between advances in the case of Thermal Radiation. The different types of causal influence (depicted in the figure by means of different kinds of arrows) will be described in Section 5.

An *advance*, therefore, is the fundamental (meta)theoretical term in the present approach. There are theoretical advances, such as ideas, formulation of problems, laws and explanations, recognition of similarities and distinctions, identification of motivations, comparison between data and theory, etc. And there are also more experimental advances, such as data acquisition, the development of experimental techniques, etc. An "advance" is not necessarily a step in the right direction, as conveyed by the usual meaning of the term. For us, advances are the units that are passed from scientist to scientist, the elements that are added to the set of ideas, data, laws, information, tacit knowledge, etc., available to a certain scientist at a specific time. Each scientist assimilates a set of advances, selects some, temporarily rejects others, combines two or more advances, etc. According to our view, science evolves based on the available advances and on the new advances imagined or discovered by theoretical and experimental scientists.

Furthermore, we stress that the advances are also *the units that would be conserved* in the passage from one possible history to another. After determining a set of advances concatenated in a network of influences for the factual history, we start postulating counterfactual histories by imagining different orderings for the *same* advances. Naturally, new advances should also be postulated for different histories.

The advances presented in Figure 1 are just a sample of those registered until now in this study. Three other important networks of influence correspond to the fields of Spectroscopy, Optical Effects, and Specific Heats of Solids (not represented here for lack of space). Besides being fundamental for the postulation of counterfactual histories, the study of advances is also interesting in itself, presenting an original picture of science and its development, as we will now see.

**4. Types of Advances.** The present approach to the dynamics of scientific theories may be considered more "empirical" (or bottom-up) than the traditional approaches. This feature is especially evident with respect to the problem of what are the *types of advances*. The almost 350 advances considered relevant in this study were arranged into around 60 types, which in turn may be grouped into ten "classes" of types. The relations occuring between these types reflect aspects of the structure of science.

In the network of advances of Figure 1, we have divided the advances roughly into five general classes (*EXPERIMENTAL TECHNIQUE*, *EXPERI-*

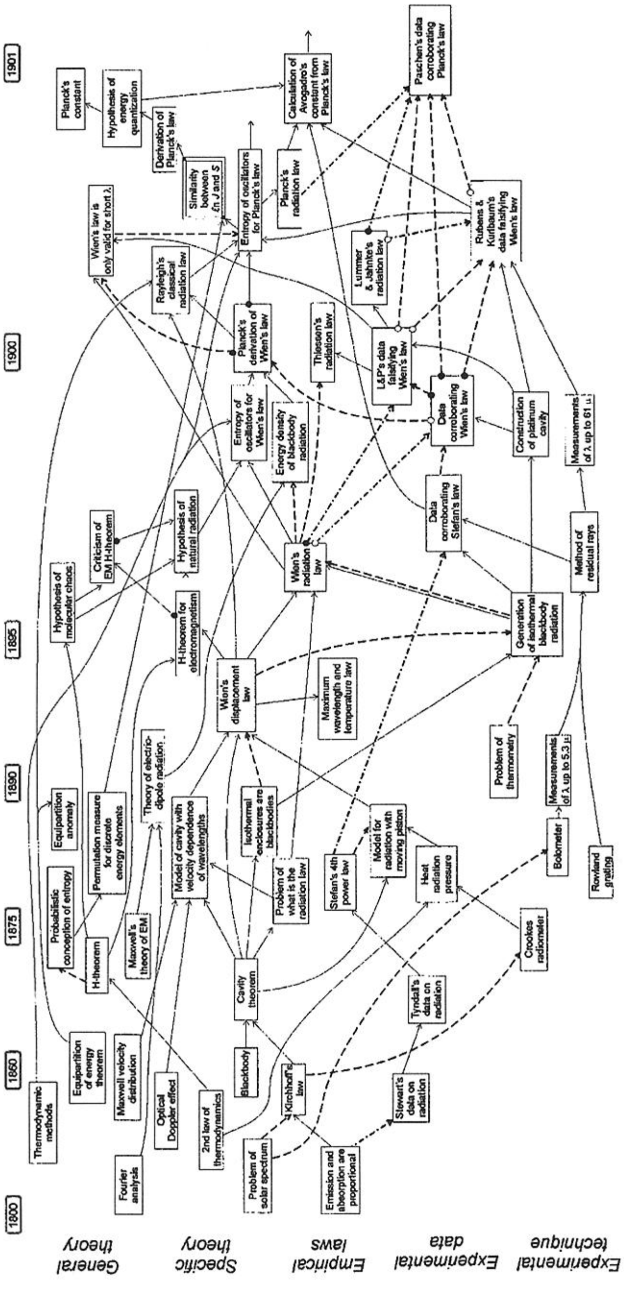


Figure 1. Network of influences between advances in the field of thermal radiation.

*MENTAL DATA*, *EMPIRICAL LAWS*, *SPECIFIC THEORY*, and *GENERAL THEORY*) along what may be called the "reality-theory axis." This *R-T axis* appears in the old "layer-cake model" of science (Feigl 1970), in which reality is represented at the bottom and the theory on top (attempting to mirror reality), while correspondence rules connect both.

The *classes* of types of advances that we propose are a little more detailed than the rough division along the R-T axis mentioned above, and are represented schematically in Figure 2. The vertical R-T axis is maintained, so that at the bottom we represent the *EXPERIMENTAL TECHNIQUES* and the *EXPERIMENTAL DATA*. On top, *THEORY DEVELOPMENT*

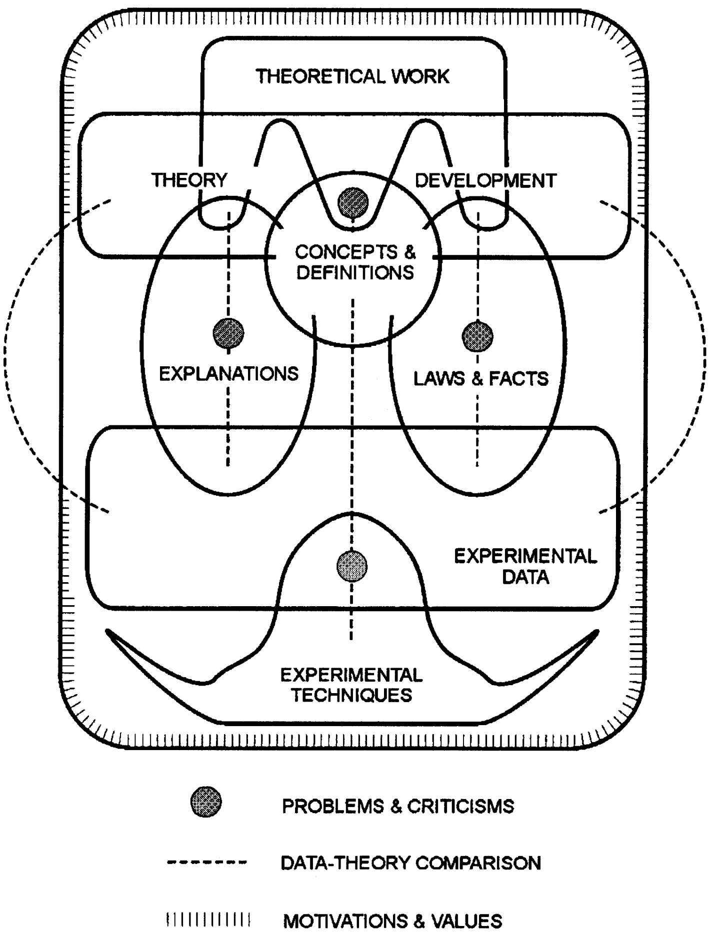


Figure 2. The "face of science," representing the classes of types of advances.

describes the growth and decadence of theories, while the *THEORETICAL WORK* consists of the *activity* of the theoretical scientist when applying formal methods to derive results and predictions. Overlapping these two classes is the class of *CONCEPTS & DEFINITIONS*, which consists of the theoretical *objects* with which the scientist works.

In the region between theory and experimental data we have placed *LAWS & FACTS*, which make a description of the world, and may also be considered objects of the theory. The comparison between theory and experiment is put in a separate class, *DATA-THEORY COMPARISON*, depicted in the figure as dashed lines which weave different aspects of theory and experiment. Parallel to the description furnished by laws, we have placed the class of *EXPLANATIONS*. Furthermore, many advances consist of the recognition of problems, which may arise in any of the classes mentioned, so they are drawn as dark circles in Figure 2. We have added to the problems the types of advances that consist of criticisms, thus forming the class of *PROBLEMS & CRITICISMS*. Finally, the class of *MOTIVATIONS & VALUES* permeates all scientific activity. An example of the type of advance that we call MOTIVATION is the recognition around 1911 that Quantum Theory was important.

**5. Types of Causal Influence.** In networks of influence between advances, such as that of Figure 1, it is important to distinguish different types of causal influence. After all, an advance $A$ which is sufficient (together with other advances) for the appearance of advance $B$ establishes a relation that is qualitatively different from the case in which $A$ only contributes circumstantially to the appearance of $B$. For the study of counterfactual histories, the first case is more important than the second.

This brings forth the fundamental distinction between two types of causal influence.

I) *Strong influence.* In Figure 1, a full arrow $A \longrightarrow B$ describes the situation in which the occurrence of $B$ was only possible because of the previous occurrence of $A$, *within a certain context*. In other words, $A$ is a necessary condition for $B$ (if $B$ occurred, then $A$ must have occurred previously). To illustrate the importance of context, let us take the example of Planck. In the context in which he was situated, the hypothesis of energy quantization could only have arisen due to the previous discovery of the "quantum theoretical" formula for the entropy of oscillators. But this does not mean that this hypothesis could not have arisen by another path, in another (counterfactual) context. We should also consider that, in general, there are multiple strong and weak causes responsible for the appearance of an advance.

II) *Weak influence.* A dashed arrow $A \dashrightarrow B$ describes the situation in which $A$ precedes and influences the occurrence of $B$, but is not a necessary condition for the occurrence of $B$. In other words, $B$ could have easily occurred without the presence of $A$, but still the fact is that $A$ had an influence on the discovery of $B$.

The demarcation between these two types is not always clear-cut. Still, while we don't have at hand a simple way of estimating the "strength" of a causal influence, we will maintain this rough distinction between strong and weak influences.

Besides this "quantitative" distinction between types of influence, there are also "qualitative" distinctions, which depend on the classes of advances being causally connected. An important example is the relation that exists between an empirical law and experimental data that confirm or disconfirm the law (in Figure 1 this type of influence is represented by an arrow with dots and dashes: $A \cdot — \cdot \rightarrow B$). To what extent may we say that the postulation of a law $A$ "causes" the acquisition of data $B$? Many times, the (contrafactual) inexistence of $A$ would lead to the non-existence of $B$. However, the acquisition of relevant empirical data could take place in an exploratory manner, without being caused by the previous postulation of a law in the same domain. In other words, even if we recognize that law $A$ strongly influenced data $B$, it is always plausible to postulate a counterfactual history in which $B$ would be obtained without the previous existence of $A$.

**6. Strategies for the Postulation of Counterfactual Histories.** After establishing a network of causal influences between advances, one may apply some *simple strategies* for visualizing different possible histories. These strategies were used up to now in an intuitive manner, but our aim in the future is to make them more rigorous, with the help of computer routines.

a) A first strategy is to assume that an apparently "improbable" advance did not occur. This is what happens with respect to the discovery of energy quantization, if we imagine that Planck had not become a physicist. We further develop this situation in (d), below.

b) Another quite simple strategy is to suppose that an advance, which in retrospect we consider "probable," such as the development of an experimental technique, had occurred before the time that in fact it did. What consequences would this anticipation bring to the "competition between possible histories"?

c) In a more restricted context, involving only a few advances (in opposition to the long chains of advances involved in the previous cases), there is a quite safe method for establishing alternative histories, which is the identification of *independent discoveries*. This term refers to the same or similar advances that occur independently. With reference to Figure 1, both Kirchhoff's law and Wien's radiation law were discovered independently in an empirical way, respectively by Stewart and Paschen. We can safely say that if Kirchhoff had not arrived at his law in 1859, this advance would have been announced to the scientific community in other ways, more specifically by the path taken by Stewart.

d) Taking the lead from (a), it is possible to formalize a strategy that supposes that the *consequence* of a fundamental discovery (in factual history) is (in a counterfactual history) the *cause* of that discovery. For example, instead of the factual history that led to quantization of energy following the path of thermal radiation, one could have a counterfactual history that followed the path of specific heats of solids at low temperatures (see point 4 in the next section).

**7. The Possible Histories of Quantum Physics.** In our preliminary study, we have glimpsed at some counterfactual histories of the appearance of the Old Quantum Theory. We have identified 4 plausible paths and 6 implausible ones.

(1) Discovery of energy quantization by means of *Thermal Radiation.* This was the path actually taken historically, represented in Figure 1. In October 1900, Planck presented his radiation law, which may be considered a genuine quantum theoretical law. Up to this point we might consider that the path taken was quite probable. What might be considered improbable was the discovery of energy quantization to explain this law, a discovery made in December 1900. Planck arrived at this hypothesis when he noticed a formal similarity between an expression for entropy that he had obtained and a formula published by Boltzmann in 1877, a formula that presupposed a discrete number of energy elements. Planck was a great scientist who rested on equally great shoulders: Boltzmann and Wien, on the theoretical side, and Lummer and Rubens, on the experimental side.

(2) Discovery of quantization by means of *Spectroscopy.* Hund suggested that this would be the most probable path to arrive at Quantum Physics. The crucial point in this development was the formulation of the Ritz combination principle (1908), together with the realization that each atom could only emit one spectral line at a time (1907). One might speculate that such advances could already have taken place around 1890 (Rydberg formulated the combination principle in 1900, but did not stress sufficiently its importance). If this had happened, what conclusions concerning the discrete nature of the atom could have been suggested? Another point to be emphasized is the concept of rotational energy quantization, which led Bjerrum (1912) to predict *equidistant* spectral lines in the infrared, which was experimentally confirmed in the following year. If such an experiment had been realized before 1900, would it have been possible to postulate an energy quantization for molecules?

(3) Discovery of quantization or wave-particle duality by means of *Op-*

*tical Effects*. In 1905, Einstein derived the quantum of light hypothesis. In spite of being influenced by Planck's quantum hypothesis, Einstein's derivation was obtained directly from Wien's radiation law (1896) and from the corresponding expression for the entropy of oscillators (derived by Planck in 1899). In other words, it would have been possible for Einstein to arrive at the quantum of light hypothesis even if Planck had not published anything concerning quantization. With his result, Einstein explained three known effects: the photoelectric effect, the granular aspect of photoionization, and Stokes' rule for fluorescence (put forth in 1852 and not explained by the wave theory of light). The photoelectric effect, by itself, could have allowed the derivation of a quantization hypothesis; an empirical version of the photoelectric law was already known in 1902, due to the work of Lenard, and was also explained by Stark (1907) by means of Planck's quantum hypothesis. The granular aspect of X rays, which appeared in the phenomenon of photoionization, had already led J.J. Thomson in 1903 to propose a discontinuous structure for electromagnetic radiation! What we must still investigate is how the experimental progress in these fields compared with the case of Thermal Radiation.

(4) Discovery of a quantum theoretical law by means of *Specific Heats of Solids*. After 1872, there was evidence that Dulong and Petit's classical law for the specific heats of solids, explained by the principle of equipartition of energy, did not work at low temperatures. The attainment of an empirical law in which the specific heats tended to zero at absolute zero (temperature) could already have taken place at that time, and such a law could constitute a genuine quantum law, such as Einstein's law in 1906. We should notice that in this work Einstein did not have to use the hypothesis of energy quantization, but only the expression for the entropy of quantum oscillators, obtained by Planck also in December 1900. It therefore could have been more probable that a quantum theoretical law for specific heats would have appeared rather than one for thermal radiation. What remains to be shown is whether it would have been as easy to start from Einstein's law and arrive at energy quantization as it was to start from Planck's radiation law.

Besides these possible paths, we have also identified a set of implausible ones, which could turn out to be possibilities with a smaller probability of occurring or could be shown to be impossible. The first three refer to the discovery of the wave-particle duality, while the latter refer to the discovery of quantization.

(5) Discovery of wave-particle duality by means of *X Rays*. The dual nature of X rays was recognized by J. J. Thomson and by W. H. Bragg in 1903–1906. A large part of the scientific community believed that X rays were electromagnetic pulses. After 1912, with the clear observation of diffraction patterns for X rays, the dualist hypothesis was abandoned. It is

conceivable, however, that the dualist hypothesis could have been widely accepted, and then the idea extended to other forms of electromagnetic radiation. It is also interesting to study how far back the discovery of X rays could have been anticipated, depending on the available technological advances.

(6) Discovery of the wave-particle duality by means of the *Mechanical-Optical Analogy*. In 1834, W. R. Hamilton developed a variational approach for both Optics and Mechanics. Geometrical optics would correspond to Newtonian mechanics; to what would wave optics correspond? Few theoretical physicists payed attention to this analogy, but after the work of L. de Broglie (1923), Debye, Madelung, and Schrödinger worked independently in the project of elaborating wave mechanics. Under what historical conditions could Hamilton's formal analogy have generated a wave mechanics, independently of the experimental observation that in fact there is a wave-particle duality?

(7) Discovery of the wave-particle duality by means of *Electrons*. The corpuscular aspect of the electron was discovered by J. J. Thomson in 1896, while the wave aspect was verified by his son G. P. Thomson (and also by Davisson and Germer) in 1927. Could the wave aspect have been observed before? Apparently not, but such a conclusion should be justified with arguments pertaining to the development of experimental techniques.

(8) Discovery of quantization by means of *Atomic and Chemical Models*. It is conceivable that the development of atomic models, together with spectroscopic data and chemical theory, could have led to the notion of quantization. Such a path should be investigated, but it does seem quite improbable. One should also notice that the discovery of tautomerism (Kekulé, Butlerov, 1860's), involving two forms of the benzene ring, was connected to the quantum mechanical notion of ressonance, as Heisenberg (1926) would later establish in his treatment of the helium atom.

(9) Discovery of quantization by means of *Magnetism*. The first quantum theory of magnetism appeared with Weiss in 1911. After Bohr's atomic model, Stern and Gerlach performed the famous experiment in which the magnetic moment of neutral atoms led to space quantization. Could the technological advances necessary for the experiment have been developed before 1900?

(10) Discovery of energy quantization by means of the *Kinetic Theory of Gases*. According to Mott (1964), the existence of discrete energy levels in atoms could have been deduced from the kinetic theory of gases and from the observation that the energy transferred to a monoatomic molecule increased only its kinetic energy, and not the energy of its internal degrees of freedom. Because of the anomalies involving the values of the specific heats of gases, Kelvin (1892) already had serious doubts concerning the validity of the law of equipartition of energy. We may also mention

that Gibbs' paradox (1898), concerning the entropy of mixtures of gases, was only explained with quantum theoretical statistics. Could these or other problems of statistical mechanics have led to the quantum postulate (in addition, of course, to Boltzmann's role in Planck's discovery)?

**8. Continuation of the Project.** The present project is still in its infancy. The most important step now is to study each article individually and improve the analysis of the networks of causal influences. Special attention will be given to the experimental and technological side, since these aspects are usually neglected in the secondary literature. We will also have to develop in a better way the strategies for postulating counterfactual histories, by improving the computer programs being used.

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