How to Identify Scientific Revolutions?

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Abstract
Conceptualizing scientific revolutions by means of explicating their causes, their underlying structure and implications has been an important part of Kuhn's philosophy of science and belongs to its legacy. In this paper we show that such "explanatory concepts" of revolutions should be distinguished from a concept based on the identification criteria of scientific revolutions. The aim of this paper is to offer such a concept, and to show that it can be fruitfully used for a further elaboration of the explanatory conceptions of revolutions. On the one hand, our concept can be used to test the preciseness and accuracy of these conceptions, by examining to what extent their criteria fit revolutions as they are defined by our concept. On the other hand, our concept can serve as the basis on which these conceptions can be further specified. We will present four different explanatory concepts of revolutions – Kuhn's, Thagard's, Chen's and Barker's, and Laudan's – and point to the ways in which each of them can be further specified in view of our concept.

Key words
Research traditions, scientific revolutions, taxonomic changes.

1. Introduction

Conceptualising scientific revolutions has been one of the central issues in the explication of scientific development in general. This topic was especially emphasised in Thomas Kuhn's *The Structure of Scientific Revolutions.* What Kuhn, as well as his successors (e.g. Larry Laudan, Paul Thagard etc.) tried to do is to offer an account of revolutions which explicates the structure underlying this process: the ways in which revolutions emerge and the changes they provoke on epistemological, methodological and ontological level. In contrast to such approaches, revolutions can also be analysed in terms of identification criteria. Let us clarify this difference by making an analogy with a medical diagnosis.

A disease can be specified in two ways. One way is to give a full explanation of the physiological processes constituting the illness. This is an account that would be useful for a biomedical researcher who wants to produces knowledge that is useful for prevention and cure. Knowing how the disease emerges and develops is useful background knowledge in such research. On the other hand, a doctor diagnosing a patient will rather refer to symptoms as the identification criteria of a disease. The full account of the disease process is irrelevant in the process of diagnosing as such. The biomedical researcher will need both approaches: if she runs clinical experiments, she will also need symptoms as identification criteria, in order to design and interpret her experiments.[1]

Going back to the case of scientific revolutions, the above mentioned attempts at characterizing revolutions are comparable to a full account of a disease process. A concept based on a set of identification criteria of revolutions – similar to a set of symptoms used for identification of a disease – is missing in the literature.[2] The aim of this paper is to offer such a concept. What we are after is a set of identification criteria, which captures the meaning of the term "scientific revolution" as it is used by scientists, historians and laypersons. In other words, there should be a substantial overlap with an intuitive usage of this term. In a broader context, our concept should also serve as a normative guideline in disambiguating and correcting the usage of the term by e.g. laypersons. We will show that such a concept can be fruitfully used not only as a tool for identifying revolutions, but for a further elaboration of already existing conceptions. To this end, we will discuss four approaches to conceptualising revolutions, given by Thomas Kuhn, Paul Thagard, Xiang Chen and Peter Barker, and by Larry Laudan.

2. How to identify scientific revolutions?

2.1. Let us first clarify how we are going to use certain concepts. A *paradigm* is a couple $<\{C_1, ... ,C_n\},\{P_1, ... ,P_n\}>$ of a set of constraints and a set of cognitive problems (research questions). The latter constitute the intended domain of application of the constraints. An *adherent* of a paradigm $<\{C_1, ... ,C_n\},\{P_1, ... ,P_n\}>$ is someone who believes that all problems in $\{P_1, ... ,P_n\}$ must be solved by using the constraints $\{C_1, ... ,C_n\}$. A *school* is a group of scientists who adhere to the same paradigm.

To clarify these definitions, consider a scientist who wants to construct a theory which accurately predicts the motion of material objects on inclined planes:

> *Cognitive problem*
> Predicting motion of material objects on inclined planes.

Let us assume that our scientist is an adherent of the Newtonian paradigm. This means that he is convinced that all kinematic problems (not only inclined planes, but e.g. also the motion of free falling bodies or of objects falling in a liquid and suspended to strings), must be solved by assuming that Newton's three laws of motion, his law of universal gravitation and his principle of vector addition of forces are correct. If we restrict ourselves to inclined planes, these general principles result in the following constraints:

> *Constraint 1*
> Any material object on an inclined plane satisfies the law $F=m\cdot dv/dt$.
> *Constraint 2*
> Any material object on an inclined plane is subject to F_Z, the gravitational force of the earth which is directed towards the centre of the earth and has magnitude $Z=m\cdot g$.
> *Constraint 3*
> If two or more forces act on the same material object, the resultant force F can be calculated by vector addition.

Because of these constraints, the initial cognitive problem is transformed into a set of more specific research questions:

> *Derived research questions*
> Which other forces influence the motion of material objects on inclined planes?
> What are the characteristics (direction, magnitude) of these forces?

The example illustrates how paradigms work: the constraints transform the general initial cognitive problem into a set of specific research questions.

2.2. Let us now present our concept of scientific revolution. First of all, the identification criteria of scientific revolutions should be capable of distinguishing revolutions (or revolutionary paradigm shifts) from gradual paradigm shifts. The way we want to draw this distinction is actually quite simple and draws on an analogy between sciences and industrial equipment. An entrepreneur owing a factory can change his production in different ways. He can e.g. expand his factory and fill the extra space with new machines. Or he can throw all his machinery and replace it completely with new ones. Scientific revolutions, as we define them, are analogous to such a complete retooling.

This is our definition:

> A revolution occurs if and only if a *substantial group* of researchers within a scientific discipline (i) shifts to a new paradigm which is such that a *large majority* of the auxiliary hypotheses of the old paradigm becomes pointless for theory building, and (ii) this group of scientists keeps on working with the new paradigm for a *certain period of time*.

Note that this definition contains some vague expressions, marked in italics. However, making these expressions more precise would be arbitrary, so we think that this set of identification criteria is “as precise as it gets”.

In order to understand this definition, it is important to know what we mean with auxiliary hypotheses. Copernicus was working with deferents and epicycles, just like the geocentrists. However, he could not recuperate their assumptions about radii and angular speeds, because they were pointless to him: they belong to constructions around the Earth rather than around the Sun. He needed brand new assumptions about radii and angular speeds. This is in sharp contrast with the paradigm shifts within a geocentric theory: Hipparchus could recuperate the assumptions of Apollonius about the radii of the circles and the angular speeds of the planets and imaginary centres of the epicycles (for a more detailed description of this example see Section 6.). In general, auxiliary hypotheses are the answers that are given to derived research questions within a paradigm (cp. Section 2.1.).

2.3. We have to establish the similarity of our concept with the intuitive use of the term. Wray 2003 contains a table of 28 scientific developments which are usually called revolutions (p. 141-142). He uses the table to test claims about the relation between age and significant discoveries. We will use it to discuss the similarity of our concept with the customary use of the term. Let us start right away with a prima facie problem. Our concept presupposes that there is a new paradigm which replaces an old one. This excludes cases in which an initial breakthrough is made in a field. The following significant scientific developments from Wray's list are not revolutions according to our definition, because there was no pre-existing alternative:

Newton	Theory of Light and Colour
Musschenbroek / Kleist	Leyden Jar
Franklin	Theory of Electrical Phenomena
Dalton	Chemical Atomic Theory
Ohm	Ohm's Law
Clausius/Kelvin	Thermodynamics
Darwin	Evolution by Natural Selection
Röntgen	X-rays

One can disagree about specific items in this list, but the idea is clear: initial breakthroughs are often called revolutions (cfr. also the so-called “axiomatic revolution” in mathematics, which refers to the first attempts to axiomatise set theory and arithmetic). These items can be opposed to cases in Wray's list where a pre-existing alternative was present:

Newton	Newtonian Mechanics	Aristotelian Mechanics
Copernicus	Heliocentric Astronomy	Geocentric Astronomy
Kepler	Elliptical Orbits	Circular Orbits
Einstein	Relativity Theory	Newtonian Mechanics
Bohr	Bohr's Atom	Thomson's Atom

The Keynesian revolution in economics, which is not in Wray's table, could be added to this list; so could the revolution in the earth sciences launched by Alfred Wegener (continental drift).

There are two ways to deal with this problem. The first is to invent different names for the two types, e.g. “domain revolution” for the first (because there is a sudden and significant change in the domain, but no dominant paradigm or research tradition that is overthrown) and “paradigm revolution” for the second type (because there is a switch from one paradigm to another). The second option is to preserve the term revolution for the second type (as we have done in our definition in Section 2.2.) and invent a new term for cases of the first type, e.g. “paradigm-creating change” (a term used in Wray 2007).

There are no fundamental objections against the first option, but we think the second one is a bit handier. Revolutions in the strict sense pose all kinds of challenges to the scientists that are involved (rational pursuit, theory choice) which are absent in episodes of paradigm-creating change. So there are a lot of problems in epistemology and philosophy of science that only relate to revolutions in a strict sense.

The identification criteria incorporated in our concept focus mainly on the difference between revolutionary and non-revolutionary changes. In contrast to conceptions of revolutions aimed at presenting the inner structure of a revolutionary change, our concept does not refer to the causes, circumstances, results, implications, etc. of revolutions. This is what makes it fruitful: it can be used to frame hypotheses about the differences (in causes, circumstances, results, implications ...) between revolutions and other scientific developments, important for the former approach to conceptualising revolutions. Let us then have a look at four different accounts of revolutionary change. We will argue that, in spite of offering important insights into the dynamics of the scientific development, each of them can be further elaborated by means of our concept.

3. Kuhn's Conceptualization of Scientific Revolutions

Distinction between *normal science* as a cumulative growth of knowledge and *scientific revolutions* as a non-cumulative growth of knowledge constitutes the main idea underlying Kuhn's conception of revolutions, or at least its negative part. The positive part is given in view of two notions: *incommensurability* and *world(-view) change* (cp. Hoyningen-Huene 1993, p. 197). The entire Kuhnian project of conceptualizing scientific revolutions could be described as an attempt at specifying these two notions in an ever more concrete way. As a result, Kuhn's later criteria of revolutionary change seem to allow for a more restrictive notion than the one given in *The Structure of Scientific Revolutions* (henceforth *TSSR*). Let us first present the main features of his early conception.

3.1. *The Structure of Scientific Revolutions: extended concept of revolutions*

The basic definition presented in *TSSR* is the following one:

> Scientific revolutions are here taken to be those non-cumulative developmental episodes in which an older paradigm is replaced in whole or in part by an incompatible new one ... (1962, p. 92)[3]

Comparing scientific revolutions with political ones, Kuhn writes:

> In much the same way, scientific revolutions are inaugurated by a growing sense, again often restricted to a narrow subdivision of the scientific community, that an existing paradigm has ceased to function adequately in the exploration of an aspect of nature to which that paradigm itself had previously led the way. In both political and scientific development the sense of malfunction that can lead to a crisis is prerequisite to revolution. (p. 92)

Kuhn calls this the genetic aspect of the parallel between scientific and political revolutions. In his view, there is also a second aspect to that parallel:

> Like the choice between competing political institutions, that between competing paradigms proves to be a choice between incompatible modes of community life (p. 94).

In which way do different paradigms resemble incompatible modes of community life? Here the concept of incommensurability enters Kuhn's account of revolutions. In the introduction of *TSSR* Kuhn writes that each scientific revolution

> ... necessitated the community's rejection of one time-honoured scientific theory in favour of another incompatible with it. Each produced a consequent shift in problems available for scientific scrutiny and in the standards by which the profession determined what should count as an admissible problem or as a legitimate problem-solution. And each transformed the scientific imagination in ways that we shall ultimately need to describe as transformation of the world within which scientific work was done. (Kuhn 1962, p. 6)

This preliminary characterisation of revolutions captures some of the main aspects of incommensurability and world-change, as they are presented in *TSSR*. Incommensurability – or a lack of common measure – is a relation which holds between pre- and post-revolutionary normal scientific practices, and it includes the following three aspects (cp. Kuhn 1962, p. 148-150; Hoyningen-Huene 1993, p. 208-212). First, the problems which are to be addressed by scientific research, as well as the standards for what counts as an acceptable problem-solution are not the same before and after a revolution. Second, there is a conceptual change or a meaning change, which can be extensional (when an object moves from the extension of one concept into the extension of another) or intensional (when the attributes of objects which fall under a concept change). Finally, 'the proponents of competing paradigms practice their trades in different worlds' (cp. Kuhn 1962, p. 150). The world[4] can change in one of the following ways: first, by an introduction of phenomena and entities which did not belong to the earlier world and which cause a revision of implicit or explicit theoretical assumptions (this class consists of unexpected discoveries such as is discovery of X-rays, cp. *Ibid.*, p. 58); second, by a transformation in which familiar objects are seen in different light, which requires an abandonment of some of their old attributes (e.g. the transition from Newtonian to Einsteinian mechanics, cp. *Ibid.*, p. 102); third, a change of certain quantitative data may change the relevant quantitative expectations or introduce some new ones (e.g. changes introduced by Dalton's work in chemistry, cp. *Ibid.*, p. 130-135).

There is indeed much more that could be said about Kuhn's concepts of incommensurability and world change. However, for the purposes of this paper it suffices to notice that they allow for a quite broad idea of scientific revolution. The concept presented in *TSSR* is an extended one when compared to the intuitive use of this term:

> The extended conception of the nature of scientific revolution is the one delineated in the pages that follow. Admittedly the extension strains customary usage. Nevertheless, I shall continue to speak even of discoveries as revolutionary, because it is just the possibility of relating their structure to that of, say, the Copernican revolution that makes the extended conception seem to me so important (p. 7-8).

The extended concept of revolution encompasses three classes of changes in scientific development (cp. Hoyningen-Huene 1993, p. 197-198). The first one includes the major shifts in scientific theory and practice, typical for the popular usage of the term (e.g. Newton's or Einstein's revolutions in physics). The second class consists of changes which have the same sorts of consequences within the relevant discipline like the first class, even though their effects might not be noticeable outside science or outside the discipline (e.g. wave-propagation theory of light or Maxwell's theory of electromagnetism). The third class consists of unexpected discoveries of new phenomena or entities, which bring corrections of previous scientific theory and practice (e.g. a discovery of X-rays).[5]

On the basis of this brief overview of Kuhn's account, we can notice that Kuhn offers no identification criteria of revolutions that would correspond to the intuitive use of this term. Clearly, our concept can be used for a further elaboration of Kuhn's conception. Using our concept we can ask, for example, if it is possible to further specify the type of incommensurability characterizing revolutions in our restricted sense, and whether it differs from incommensurability in other types of scientific developments. As a matter of fact, according to some interpreters, Kuhn's later specification of the notion of incommensurability allows for the notion of revolution that is more similar to the popular term. Let us then present Kuhn's later criteria.

3.2. *Revolutions as taxonomic changes*

3.2.1. In the course of his later work, Kuhn turned towards linguistic aspects of scientific developments, specifying the notion of revolution in terms of taxonomic changes. In Kuhn 1987 scientific revolutions are presented as sharing the following key properties:

(1) Revolutionary changes are *holistic*: in contrast to cumulative changes where a single generalization can be added or revised, 'in revolutionary change one must either live with incoherence or else revise a number of inter-related generalizations together.' (Kuhn 1987, p. 29). This holistic character of revolutionary changes derives from a specific type of meaning change, which is Kuhn's next criterion.

(2) Revolutions are characterised by a *meaning change* – a change in the way words and phrases attach to nature, i.e. a change in the way their referents are determined. Since this criterion is too broad, the following one serves as its specification.

(3) Revolutionary changes alter not only the criteria by which terms attach to nature but also *the set of objects or situations* to which those terms attach. In other words, the meaning change has to be such that it induces a *world-change*.

These key properties are summarized in the following quote:

> What characterizes revolutions is, thus, change in several of the taxonomic categories prerequisite to scientific descriptions and generalizations. That change, furthermore, is an adjustment not only of criteria relevant to categorization, but also of the way in which given objects and situations are distributed among preexisting categories. Since such redistribution always involves more than one category and since those categories are interdefined, this sort of alteration is necessarily holistic. (Kuhn 1987, p. 30)[6]

Furthermore, in his (1991) Kuhn restricted taxonomic changes relevant for scientific revolutions to the class of kind terms:

> Terms of this sort have two essential properties. First, ... they are marked or labeled as kind terms by virtue of lexical characteristics like taking the indefinite article. Being a kind term is thus part of what the word means, part of what one must have in head to use the word properly. Second – a limitation I sometimes refer to as the no-overlap principle – no two kind terms, no two terms with the kind label, may overlap in their referents unless they are related as species to genus. There are no dogs that are also cats ... Therefore, if the members of a language community encounter a dog that's also a cat (or more realistically, a creature like a duck-billed platypus), they cannot just enrich the set of category terms but must instead redesign a part of the taxonomy. (p. 92)

The main ingredient of Kuhn's later account are thus changes in the taxonomy of kind terms specific for the scientific discipline in question. In contrast to the account of incommensurability given in *TSSR,* taxonomic change is not anymore just one aspect of incommensurability, but it has become its crucial property. This shift derives from Kuhn's explication of the notion of incommensurability in terms of translatability. Namely, in the context of scientific theories "no common measure" receives the meaning of "no common language":

> The claim that two theories are incommensurable is then the claim that there is no language, neutral or otherwise, into which both theories, conceived as sets of sentences, can be translated without residue or loss. (Kuhn 1983, p. 36)

Characterized in this way, incommensurability does not require that languages of two competing paradigms differ in all of the concepts. In most cases incommensurability is *local*, which means that 'Only for a small subgroup of (usually interdefined) terms and for sentences containing them do problems of translatability arise.' (Kuhn 1983, p. 36) Moreover, incommensurability and world-change occur only when the *structure of the lexicon*, consisting of the relations between empirical concepts of a discipline, changes (cp. Kuhn 1983, p. 52; Hoyningen-Huene 1993, p. 217-218). Clarifying the difference between his early and later approach Kuhn writes:

> In *Structure* [TSSR] it [the distinction between normal and revolutionary development] was the distinction between those developments that simply add to knowledge, and those which require giving up part of what's been believed before. In the new book it will emerge as the distinction between developments which do and developments which do not require local taxonomic change. (The alteration permits a significantly more nuanced description of what goes on during revolutionary change than I've been able to provide before.) (Kuhn 1991, p. 97)[7]

Interestingly, Kuhn sometimes makes a difference between the concept of revolution based on its identification criteria and his broader, explanatory concept. In his article *What are Scientific Revolutions?* (Kuhn 1987) Kuhn gives several examples of revolutions, and discusses characteristics which they all share. Before presenting the examples he writes:

> Before turning to a first extended example, let me try – for those not previously familiar with my vocabulary – to suggest what it is an example of. Revolutionary change is defined in part by its difference from normal change, and normal change is ... the sort that results in growth, accretion, cumulative addition to what was known before. Scientific laws, for example, are usually products of this normal process: Boyle's law will illustrate what is involved. Its discoverers had previously possessed the concepts of gas pressure and volume as well as the instruments required to determine their magnitudes. … Revolutionary changes are different and far more problematic. They involve discoveries that cannot be accommodated within the concepts in use before they were made. (p. 14)

Kuhn here obviously makes an attempt at offering the identification criteria of scientific revolutions. Nevertheless, these criteria are not very precise since the distinction between cumulative and non-cumulative changes is not sufficiently explicated. Moreover the explication of this distinction necessarily requires Kuhn's broader analysis of revolutions. In other words, his identification criteria cannot stand on their own: their full understanding requires Kuhn's explanatory concept of revolution. Such broadly construed identification criteria could of course be accurate, but their complexity makes them less handy than the criteria offered by our concept. Moreover, the overlap between the concept of revolution captured in Kuhn's later writings and the intuitive usage of the term is not completely clear. On the one hand, Kuhn never explicitly said that his later concept is more restrictive than the one in *TSSR* (cp. Wray 2007, p. 64). On the other hand, according to some interpreters, his later conception allows for this restriction. By comparing his criteria to our concept, we could obtain an answer to this question. In contrast, without specifying the identification criteria of revolutions, an analysis of late Kuhn's notion and its similarity to the popular term remains imprecise. Let us clarify this on the example of Wray's interpretation.

3.2.2. Taking into account Kuhn's later explication of the notion of incommensurability, Brad Wray (2007) suggests that the necessary and sufficient conditions for Kuhnian revolutions can be summarized in the following way:

> For a scientific revolution to occur, (i) a research community must make a taxonomic change, (ii) the change must undermine the shared standards of the research community, and (iii) there must be a widespread disappointment with existing practices. (Wray 2007, p. 66)

Wray shows that by requiring that a revolutionary change includes a replacement of one taxonomy by another incommensurable one, Kuhn implicitly narrowed down his original concept (cp. Wray 2007, p. 67-68). For example, discovery of X-rays, which fitted Kuhn's earlier criteria as the case of an unexpected discovery (cp. Hoyningen-Huene 1993, p. 229), does not fit his later criteria, since it did not cause a replacement of the existing taxonomy with a new incommensurable one (cp. Wray 2007, p. 68).

It is important to notice that Wray does not offer any identification criteria of revolutions, which would clarify why discovery of X-rays is not to be considered as a scientific revolution (according to the customary use of the term). He only shows why this discovery does not fit Kuhn's later criteria of revolutions, but in how far these criteria fit the popular term is shown only by means of several examples, and not by any clear concept of the popular term. The identification criteria incorporated in our concept can be of help here. For example, in view of our concept, it is easy to see why the discovery of X-rays was not a scientific revolution: it did not induce a rejection of the majority of then accepted auxiliary hypotheses (cp. Section 2.2).

Moreover, our concept can be used to test the accuracy of Kuhn's criteria as Wray's conceives them. For example, on the basis of it we can show that the requirement for a crisis might not be satisfied by all historical cases.[8] Let us have a look at the example of the recent revolution in geological sciences.

The revolution in geology, which was initiated by Wegener's hypothesis of the continental drift and concluded by the general acceptance of the theory of plate tectonics was not preceded by a crisis, which is in Wray's interpretation, one of the necessary and sufficient conditions of Kuhnian revolutions. The reason for this lies in the specific state of geological sciences before the revolution. Before the theory of plate tectonics geology did not have the usual properties of Kuhnian normal science. It was divided in sub-disciplines (such as seismology, experimental petrology, structural geology, oceanography), each of which had its own set of problems and methods for addressing them. The only common element of all these approaches was the assumption of stable continents, which itself was too less to unite them under the same framework of the normal scientific research in Kuhnian sense of the term (cp. Stewart 1990, p. 138-139; Hallam 1973, p. 107-108). However, it would be equally wrong to characterize such a state as a pre-paradigm state of science, since each of these disciplines alone did have the properties of normal science. We could rather describe it, together with John A. Stewart, as a *multi-paradigm* state of science (cp. Stewart 1990, p. 139). Stewart here calls upon Margaret Masterman's point that ‘multi-paradigm science is full science, on Kuhn's own criteria, by the proviso that these criteria have to be applied by treating each sub-field as a separate field’ (Masterman 1970, p. 74). In such a situation the assumption of fixed continents, although common to most geologists, did not have serious implications for the oceanographic data, which brought the key evidence for the plate tectonics hypothesis. Even when there were expectations regarding this data, it was easy to modify supporting assumptions in order to get the right match (Stewart 1990, p. 142). Therefore, there was no real crisis, but instead, there was a growing awareness that the new theory could serve as the general framework for all geological disciplines. Nevertheless, the majority of auxiliary hypotheses constituting the “fixist” framework had to be rejected and replaced by the new theory of plate tectonics, which means this shift was indeed revolutionary according to our concept.

4. Thagard's conceptual revolutions

Following Kuhn's taxonomic approach to conceptualizing revolutions, Thagard (1992) offered an account which links scientific revolutions to revisions of ontology, characterised in terms of conceptual systems. Let us first explicate the notion of a conceptual system as it is used in this context.

Conceptual systems can be analysed as networks of concepts which stand in certain relations. These relations include (cp. Thagard 1992, p. 30-31):

(1) *Kind links*, which indicate that one concept is a kind of another. For example, black is a kind of colour, a reptile is a kind of animal.
(2) *Instance links*, which indicate that the object represented by a concept is an instance of another concept. For example, Tweety is a bird, Tweety is a canary.
(3) *Rule links,* which express general (but not always universal) relations among concepts. For

example, canaries have the colour yellow.

(4) *Property links*, which indicate that the object represented by a concept has a property captured by another concept. For example, Tweety is yellow.

(5) *Part links,* which indicate that a whole has a given part. For example, A beak is a part of a bird.

In view of such a representation of conceptual systems, Thagard suggests that ontologies can be specified in terms of kind and part links.

> Why are kind-relations and part-relations so fundamental to our conceptual systems? In addition to the organizing power of the hierarchies they form, these two sets of relations are important because they specify the constituents of the world. *Ontology* is the branch of philosophy (and cognitive science!) that asks what fundamentally exists, and ontological questions usually concern what *kinds* of things exist. Moreover, given an account of the kind of things there are, which translates immediately into a hierarchical organization, we naturally want to ask: of what are the objects of these kinds made? The answer to this question requires consideration of their parts, generating the part-hierarchy that also organizes our concepts. Thus the major role that kind-hierarchies and part-hierarchies play in our conceptual systems is not accidental, but reflects fundamental ontological questions. (Thagard 1992, p. 32-33; italics in original)

Even though Thagard does not speak of instance links at this place, we find them equally important for the specification of ontology he is after. For example, without instance links it would be difficult to show the difference between the ontologies underlying geocentric and heliocentric standpoints, since the assumption that the Sun is an instance of a planet is a link present in the former but not in the latter conceptual system.

Let us now look at the various ways in which ontologies can change (cp. Thagard 1992, p. 34-36). If a new ontology is formulated, it may happen that links are added but *no links are deleted*. In this case, the new ontology is an *extension* of the old one. Three "pure" subtypes can be distinguished here (mixtures of these types are also extensions). The first subtype is what Thagard calls *decomposition*. The ontologies of Bohr and Heisenberg constitute a good example. Bohr's ontology can be characterised as follows:

Atoms consist of a nucleus and one or more electrons.
Nuclei and electrons are indivisible wholes.

Heisenberg dismisses the last claim and replaces it with:

Electrons are indivisible wholes.
Nuclei consist of protons and neutrons.
Protons and neutrons are indivisible wholes.

Two concepts and two part links are added, and no part link (or other link) is removed.

The two other pure types which Thagard distinguishes are *coalescence* and *differentiation*. In the first, a superordinate concept is added to group two concepts previously thought to be unrelated. Kind links are added between the existing concepts and the new one. For instance, one can introduce the concept of living being to group animals and plants. Differentiation works the other way around: subordinate kinds are distinguished.

If at least one link is deleted and replaced with another one, the ontology is *revised*, not merely extended. We discuss some important subtypes. The first one is what Thagard calls *collapse*. This is the reverse of differentiation: concepts falling under the same superordinate concept disappear. For instance, Newton abandoned the Aristotelian distinctions between terrestrial and celestial bodies, and between natural and unnatural motions. It is obvious that a collapse entails that kind links are deleted.

In the second subtype, no concepts are deleted: the existing concepts are reorganized. In the Darwinian revolution, kind links were reorganised. Before Darwin, there were three kinds of living creatures: human, animal and plant. After Darwin humans cease to be a separate category: they are kinds of primates, primates are kinds of mammals and mammals are kinds of animals. Thagard calls this *branch jumping*, because concepts move from one branch of the tree (which can be used as graphical representation of the conceptual system) to another branch.

Similar things can happen with part links. In Stahl's Phlogiston Theory, metals consist of calx and phlogiston; phlogiston and calxes are elements. According to Lavoisier, calxes consist of metal and oxygen; metals and oxygen are elements. What we have here is the addition of a new concept (oxygen, resulting in a new branch representing the decomposition of calxes), deletion of a concept (phlogiston, resulting in the collapse of the decomposition branch of metals) and reorganization (metals become parts of calxes, instead of the other way around; this is similar to branch-jumping).

Finally, instance links can be revised. For instance, the conceptual system of geocentrist and heliocentrist astronomers contains the following part links.

> The Universe contains planets.
> The Universe contains the Stellar Sphere.
> The Universe contains the Sun, the Earth, the Moon, Mercury, Venus, Mars, Jupiter, and Saturn.

The characteristic instance links accepted by the geocentrist, are:

> The Sun is a planet.
> The Moon is a planet.
> The Earth is not a planet.

Heliocentrists introduce a new concept (satellite), so a part link is added:

> The Universe contains satellites.

This addition is just an extension. The revisions occur in the instance links:

> The Sun is not a planet.
> The Moon is a satellite.
> The Earth is a planet.

These links, accepted by the heliocentrist, contradict the geocentric ones mentioned above.

Though Thagard does not claim that all revisions of ontology lead to revolutions, he sees a strong link:

> Because kind-relations organize concepts in tree-like hierarchies, a very important kind of conceptual change ... involves moving a concept from one branch of the tree to another. Such *branch jumping* is *common* in scientific revolutions. (p. 36; italics on “common” added)

> Belief revision, concept addition, and simple organization of conceptual hierarchies are common in the development of scientific knowledge, but we shell see that branch jumping and tree switching are much rarer events *associated* with conceptual revolutions. The momentousness of a revision is affected, of course, by more than these conceptual relations. (p. 37; italics added)

> [Scientific revolutions] differ in the kinds of conceptual change that they involved, although all major revolutions in the natural sciences *include* the most dramatic kinds of conceptual change: branch jumping or tree switching. (p. 262-263; italics added)

The first two quotes suggest that revisions belong to the typicality of scientific revolutions (where revisions are neither necessary nor sufficient for revolutions), while the last quote suggests that revisions are a necessary condition for all *major* revolutions. In both cases, the notion of scientific revolution is not clearly identified. Moreover, the distinction between “major” and “non-major” revolutions, assumed in the last quote, is not at all explicated.

Our definition of revolutions can be used to explore the link between revisions and scientific revolutions in more detail. Consider two paradigms *A* and *B*, where *B* is developed to replace *A*. If the ontology of *B* is a revision of *A*, then it often happens that the auxiliary hypotheses of A are pointless for theory building from the perspective of the new paradigm. The shift from geocentric to heliocentric astronomy illustrates this. However, not all revisions lead to revolutions. For example, according to a new convention in astronomy, Pluto is not to be characterised as a planet. The kind link has thus been changed (an instance of *branch jumping*) and a new ontology is constructed, without any revolutionary implications.

If the ontology of *B* is identical to or an extension of *A*, it often happens that most of the auxiliary hypotheses of A can be used in theory building within the framework of paradigm *B*. This is illustrated by the successive paradigms within the geocentric tradition. However, there are exceptions. Kepler's introduction of elliptical orbits constitutes a scientific revolution (according to our definition) without revision of ontology. Heisenberg's model of the atom is another example: the ontology remains the same (an atom consists of a nucleus and electrons) but the hypotheses about the behaviour of the atoms are completely different compared to Bohr's atomic model. Revolutions thus can be triggered without tinkering with the ontology of a paradigm.

5. Chen's and Barker's frame-based approach to taxonomic changes

According to Kuhn's original conception of revolutions, revolutionary changes occur in a discontinuous manner.[9] Contrary to this, Chen and Barker have argued that scientific revolutions often exhibit strong continuity (Chen et al., p. S209). Using methods from cognitive psychology they offered a model of conceptual change in order to show that ‘if concepts are represented by frames, the changes characteristic of scientific revolutions, especially taxonomic changes, can occur in a continuous manner’ (Chen et al. 2000, p. S209).

A frame representation used in this model consists of: a) a superordinate concept, b) two lists of properties – attributes and values – which can be ascribed to this concept, and c) a list of subordinate concepts. All the subordinate concepts share the properties in the attribute list, while only some properties from the value list represent their typical features. For example, the superordinate concept of fowl has five attributes: beak, neck, body, leg and foot. Each of these attributes has a set of ascribable values: a beak can be either rounded or pointed, a neck can be either short or long, etc. By choosing a round beak and short legs, we obtain typical features of the subordinate concept – waterfowl, while a pointed beak and long legs give us the subordinate concept – game bird (cp. Chen et al. 2000, p. S210). A frame constructed in this way is capable of capturing certain relations between the concepts and their typical features, namely:

(1) Hierarchical relations between the features of a concept: some features are attributes while others are only values ascribable to some of the attributes and not directly to the concept itself. For example, “large” is a value which can characterize the attribute “body” – one of the properties of the superordinate concept of fowls.
(2) Stable relations between the attributes, i.e. relations which hold across all typical exemplars of the superordinate concept. For example, “body” and “neck” stand in a relation which is a structural invariant for the class of fowls.
(3) Constraints on the relations between the values and attributes, i.e. on their variability (e.g. in the case of fowls, there is a constraint between the values of “leg” and “body” – long legs are usually associated with a large body) (cp. Chen et al. 2000, p. S210-S211).

The main advantage of this approach to taxonomic change analysis is that it can account for the continuity of a change during scientific revolutions:

> Every single classification anomaly immediately causes changes in the frame of the superordinate concept and then changes in the taxonomy. Both the changes of frame and those of taxonomy are continuous. ... At a certain point in this piecemeal evolution, the newly formed taxonomy becomes incompatible with the old one, and then the revolutionary nature of this continuous change becomes recognizable. (Chen et al. 2000, p. S216)

In spite of the advantages of Chen's and Barker's model, we may notice that it offers no clear criteria for distinguishing between scientific revolutions and smaller changes in scientific development. In other words, it does not answer the question: at which point in this piecemeal evolution the change becomes revolutionary? As the authors (together with Hanne Andersen) clarify in another paper discussing the same model:

> A central contrast in Kuhn's original work is the division between normal and revolutionary science. We may now understand this division as the distinction between research conducted in terms of an existing conceptual structure, without changing that structure, and research proceeding by modifying an existing conceptual structure ... (Barker et al. 2003, p. 232)

But as we have already shown (in Section 4), conceptual change *as such* is not a sufficient condition for a scientific revolution, since not all types of conceptual change lead to revolutions. As a result, Chen's and Barker's account is not capable of offering identification criteria of revolutions. Our concept can be fruitfully used for a further specification of conceptual changes presented by this model. For example, in view of our concept, it could be asked: at which point does a conceptual change (presented in terms of this model) become revolutionary (according to our identification criteria)? Which features need to be added to the model so that it can account for the distinction between scientific revolutions and other changes in scientific development?

6. Laudan's Conception of Scientific Revolutions

Laudan (1977) introduces the concept of *research tradition* to describe the evolution of scientific disciplines. The working definition which he proposes is:

> A research tradition is a set of general assumptions about the entities and processes in a domain of study, and about the appropriate methods to be used for investigating the problems and constructing the theories in that domain. (1977, p. 81)

So research traditions are sets of ontological and methodological commitments. However, this set is not fixed. There is a gradual evolution:

> There is much continuity in an evolving research tradition. *From* one stage to the next, there is preservation of most of the crucial assumptions of the research traditions. But the emphasis here must be on *relative* continuity between *successive* stages in the evolutionary process. If a research tradition has undergone numerous evolutions in the course of time, there will probably be many discrepancies between the methodology and the ontology of its *earliest* and its *latest* formulations. (1977, pp. 98-99; italics in original)

Each successive stage of a research tradition is a certain set of ontological, axiological and methodological guidelines. This can be illustrated by means of a fragment (from Apollonius over Hipparchus to Ptolemaeus) of the history of geocentric astronomy.

The ontology on which these three astronomers built their theories has two basic claims:

(G_A) The Earth is located in a sphere (the Stellar Sphere) to which the fixed stars are attached.

(G_B) Besides the Earth, the Stellar Sphere contains seven celestial bodies that are called planets (Greek for wanderers) because they *seem to* move in an irregular way. These planets are: Moon, Sun, Mercury, Venus, Mars, Jupiter en Saturn.

In the third century B.C, Apollonius developed a theory which could predict the motion of the stars and the planets by implementing the following guidelines:

(G_1) The Earth is stationary: it does not participate in any locomotion.
(G_2) The Earth is located at the centre of the Stellar Sphere.
(G_3) The Stellar Sphere rotates at constant speed around the earth.
(G_4) The motion of planets is *epicyclic*: they are located at the circumference of a circle (called the *epicycle*) whose centre D also makes a circular motion around some centre (the latter circle is called the *deferent*).
(G_5) The Earth is the centre of the deferents of all planets.
(G_6) The two circular motions are uniform: the centres of the epicycles move at constant speed around the Earth, and the planets move at constant speed around the centre of their epicycle.

Implementation of these guidelines requires determining the values of the two radii and of the two angular speeds of motion. A good implementation of Apollonius' paradigm[10] can explain retrograde motion and can account for the fact that planets appear brighter at some times than at others. However, there were some unsolvable problems, e.g. the fact that the Sun looks larger at noon in the (Greek/Northern) winter than in summer. This and other problems were solved in the second century B.C. by Hipparchus of Nicaea, who introduced *eccentric motion*. His paradigm contains the ontological claims G_A and G_B, and all laws except G_5 and G_6 are conserved. G_5 is replaced by:

(G_5') For each planet there is a point E, the *eccentric*, which is the centre of its deferent. This centre is not necessarily the Earth.

The double uniformity idea of G_6 is retained, but the formulation must be adapted as a consequence of the shift from G_5 to G_5'. The new formulation is:

(G_6') The two circular motions are uniform: the centres of the epicycles move at constant speed around the eccentric E, and the planets move at constant speed around the centre of their epicycle.

To implement this new paradigm, we have to determine the values of the radii and the angular speed (as was the case with Apollonius). On top of that, we have to determine the positions (relative to the Earth) of the eccentrics of the different planets.

In the second century A.D., Claudius Ptolemaeus of Alexandria developed a device, the *equant*, for eliminating the remaining inaccuracies in the predictions of the theory of Hipparchus. He gave up G_6' and replaced it with:

(G_6'') (a) For each planet there is a point Q, the *equant*, such that the angular speed of D (the centre of the epicycle) is constant with respect to Q. Q is not necessarily the eccentric E or the Earth.
(b) The planets move at constant speed around the centre of their epicycle.

Now let us see how Laudan defines scientific revolutions. He writes:

> [A] scientific revolution occurs when a research tradition, hitherto unknown to, or ignored by, scientists in a given field, reaches a point of development where scientists in the field feel obliged to consider it seriously as a contender for the allegiance of themselves or their colleagues. (1977, p. 138)

This definition would be adequate if Laudan had a clear criterion for distinguishing research traditions from one another. He does not have such a criterion. So Laudan's criterion does not say anything about what is going on in a revolution, and how we can recognize one when we see one. For instance, Copernicus used the same methods (deferents and epicycles) as the geocentrists. So why is this a new research tradition? Laudan does not give any answer. Our concept can be used to help answering this question. In view of it, we can say that Copernicus could not recuperate the auxiliary hypotheses of the geocentrists. He had to start all over again, had to build a completely new system.

7. Conclusion

In this paper we have presented a concept of scientific revolution based on its identification criteria. Such a concept is to be distinguished from approaches to conceptualising revolutions which aim at explaining different aspects of the whole process, and which we have dubbed as explanatory concepts of revolution. The aim of this paper was to show not only that there is a difference between these two approaches, but that the identification criteria of revolutions can be fruitfully used for a further elaboration of conceptions of the second type. On the one hand, we can use our concept to test the preciseness and accuracy of the explanatory conceptions, by examining to what extent their criteria fit revolutions as they are defined by our concept. On the other hand, our concept can serve as the basis on which different approaches to conceptualising revolutions can be further specified. By presenting four different explanatory concepts of revolutions, we have pointed to the ways in which each of them could be further elaborated in view of our concept.[11]

Notes

1. Note that this is also the limit of our analogy: the identification criteria are not the same as symptoms. The notion of symptom is both broader and narrower than the notion of an identification criterion: broader since symptoms are not always sufficient for a clear identification of a phenomenon, and narrower since, in contrast to identification criteria, one and the same set of symptoms might not be applicable to all the instances of a whole class of phenomena.
2. In order to make it easier to follow which of these two approaches we are referring to, we will call the first type “explanatory concepts of revolutions”.
3. All citations of TSSR will be given according the the 3rd edition from 1996.
4. Kuhn's notion of world should not be confused with a realist concept of the mind-independent world. For a detailed discussion on this concept in Kuhn's work see Hoyningen-Huene 1993, Section 6.2, as well as Šešelja et al. forthcoming, Section 4.
5. Hoyningen-Huene remarks that ‘this step doesn't extend the meaning of the noun '(scientific) revolution' but only of the adjective 'revolutionary'. For while, in his writings, Kuhn qualifies discoveries in the appropriate class as 'revolutionary', he usually doesn't call them revolutions’ (Hoyningen-Huene 1993, p. 1998). Nevertheless, it would be farfetched to say that Kuhn had a clear view on the distinction between “scientific revolution” and “revolutionary change” or that he coherently applied it in TSSR (see, e.g., Kuhn 1962, p. 92-93 where he explicitly mentions discovery of X-rays as an example of a scientific revolution in the extended sense of the term). We will thus keep on using these two terms (“revolution” and “revolutionary change”) interchangeably.
6. Note that Kuhn's point is not that revolutionary changes do not consist of piece-meal changes, but that during such stages scientific theories are necessarily incoherent, and that ‘only the initial and final sets of generalizations provide a coherent account of nature’ (Kuhn 1987, p. 29).
7. Beside the mentioned criteria, Kuhn adds that his taxonomic approach points to the fact that revolutions should be compared with “speciation”: ‘After a revolution there are usually (perhaps always) more cognitive specialties or fields of knowledge than there were before.’ (Kuhn 1991, p. 97; also cp. Kuhn 1993, p. 250-251).

8. Note that even Kuhn himself weakened the idea of crisis as a necessary prerequisite to revolutions: even though, according to his conception, a revolution is usually preceded by a crisis, ‘Revolutions may also be induced in other ways, though I think they seldom are.’ (Kuhn 1962, p. 181; cp. also Hoyningen-Huene 1993, p. 232-233). In so far, Wray's criteria are not the most accurate representation of Kuhn's thought.
9. This property of revolutions has been modified in Kuhn's later articles where he speaks of revolutionary changes as holistic rather than discontinuous (cp. Note 5).
10. The term “paradigm” is used here to denote a stage of a research tradition.
11. Our concept also makes it possible to investigate the relation between revolutions and creativity and the relations between revolutions and rationality. See Weber 1999 for this.

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