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SCIENTIFIC REVOLUTIONS, RATIONALITY AND CREATIVITY[1]

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1. Introduction

The aim of this article is to answer three questions with respect to the evolution of scientific disciplines:
(1) Are scientific revolutions important for the growth of science?
(2) Can the choice to pursue one line of research rather than another, ever be rational? Or are such choices always arbitrary?
(3) Are revolutions the creative moments in science? Do they require creativity, while gradual change is possible without creativity?
I will discuss these questions in sections 5-7. Sections 2-5 prepare this discussion. Section 2 contains some definitions. Sections 3 and 4 summarise the views of Thomas Kuhn, Imre Lakatos and Larry Laudan on the evolution of scientific disciplines. We will use this material to clarify and refine the questions (especially the first and second).

2. Some definitions

I first clarify how I use certain key concepts in this article. A *paradigm* is couple $<\{C_1,\ldots,C_n\},\{P_1,\ldots,P_n\}>$ of a set of constraints and set of cognitive problems (research questions). The latter constitute the intended domain of application of the constraints. An *adherent* of a paradigm $<\{C_1,\ldots,C_n\},\{P_1,\ldots,P_n\}>$ is someone who believes that all problems in

[1] I thank Maarten Van Dyck for his comments on a previous draft of this paper.

$\{P_1,\ldots,P_n\}$ must be solved by using the constraints $\{C_1,\ldots,C_n\}$. A *school* is a group of scientists who adhere to the same paradigm[2].

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 $\mathbf{F}=m\times d\mathbf{v}/dt$.
> *Constraint 2*
> Any material object on an inclined plane is subject to $\mathbf{F}_Z$, the gravitational force of the earth which is directed towards the centre of the earth and has magnitude $Z=m\times g$.
> *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:

[2] It is well known that Kuhn, who introduced the paradigm concept in philosophy of science, used this term in a very ambiguous way. My definition is chosen in such way that a clear comparison of the views of Kuhn, Lakatos and Laudan is possible by means of this concept.

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.

3. Kuhn and Lakatos on the evolution of scientific disciplines

3.1 Thomas Kuhn

The core of Kuhn's view on the evolution of scientific disciplines can be represented as follows:

(K_1) In all mature scientific disciplines, there are long periods in which one paradigm monopolises this discipline (almost) completely.
(K_2) When a paradigm looses its monopoly, it is replaced with an alternative that differs radically from it.
(K_3) Paradigm shifts are irreversible: once a paradigm has lost its adherents, it will never become dominant again.
(K_4) In periods between revolutions, scientists solve cognitive problems which belong to the intended domain of the paradigm.

The evolution of mechanics fits this scheme very well. From the end of the 17th century till the beginning of the 20th century, the Newtonian paradigm monopolised this discipline. Furthermore, it was radically new. The most important differences with its Aristotelian predecessor are:
(1) In Newton's view there is only one inertia principle, valid for all material objects: objects on which no force is exerted, move rectilinearly at a constant velocity. Aristotle has two such principles, one for celestial bodies (they move in circles if no force is exerted on them) and one for terrestrial bodies (they move to their natural places if no force is exerted on them).

(2) In Aristotle's view, a body can exert a force on another body only if there is spatial contact between them. By introducing gravitation, Newton invokes *actio in distans*.

Finally, scientists after Newton were engaged in applying the paradigm to kinematic problems that Newton himself did not discuss. Newton applied his paradigm only to free falling bodies and the motion of the planets. All other kinematic problems were treated later by other physicists.

3.2 Imre Lakatos

Lakatos calls his theory of the evolution of scientific disciplines "the Methodology of Scientific Research Programmes". These *research programmes* are sets of constraints on how to solve problems in a domain. So they are paradigms as defined in section 2, and the terms can be used interchangeably (as Lakatos suggests in the quotation below). However, there are two topics on which Kuhn and Lakatos disagree completely.

To begin with, Lakatos has argued that K_1 is wrong:

> Unfortunately, this is the position which Kuhn tends to advocate: indeed, what he calls 'normal science' is nothing but a research programme that has achieved monopoly. But, as a matter of fact, research programmes have achieved complete monopoly only rarely and for short periods, despite the efforts of some Cartesians, Newtonians and Bohrians. *The history of science has been and should be a history of competing research programmes (or, if you wish, paradigms), but has not been and must not become a succession periods of normal science: the sooner competitions starts, the better for progress.* (1970, p. 155; italics in original)

If we give up K_1, K_2 cannot be literally true anymore: there are no monopolies. However, Lakatos retains the idea of radical differences: the competing research programmes are fundamentally different.

Given this first disagreement, Lakatos could defend a modified version of K_3:

(K_3') If a research programme is forced into a minority position, it can never become the favourite of the majority again.

However, he does not defend this position:

> One must realise that one' opponent, even if lagging badly behind, may still stage a comeback. No advantage for one side can ever be regarded as absolutely conclusive. There is never anything inevitable about the triumph of a programme. Also, there is never anything inevitable about its defeat. (1971, pp. 118-119)

Lakatos' emphasis on the reversibility of dominance constitutes the second important disagreement.

Besides these two repudiations, Lakatos also refines Kuhn's analysis. A research programme is characterised by a *hard core* to which auxiliary hypotheses are added to solve cognitive problems. Lakatos emphasises that the system of auxiliary hypotheses (which he calls the *protective belt*, because they protect the hard core from falsification) evolves. One of his examples is an imaginary case of planetary misbehaviour (1970, pp. 100-101). A Newtonian physicist combines the hard core of the Newtonian research programme (his three laws of motion, the law of gravitation and vector addition) with auxiliary hypotheses A to calculate the path of a newly discovered small planet. Observations show that the planet deviates from the calculated path. To account for this discrepancy, an extra hypothesis is added to A: the path of our newly discovered planet is disturbed by a hitherto unknown planet. If this disturbing planet cannot be found, the Newtonian can add another hypothesis: a cloud of cosmic dust hides the disturbing planet from us. Though such dynamic does not contradict K_4, Lakatos' emphasis on it constitutes a refinement: Kuhn emphasises that paradigms evolve because scientists solve puzzles (i.e. theories for previously untreated cognitive problems are added) but neglects the fact that the solutions for the puzzles evolve and tend to become more complex.

4. Larry Laudan on the evolution of scientific disciplines

4.1 Example

In his 1977 Larry Laudan introduces the concept of *research tradition* to describe the evolution of scientific disciplines. Before giving his definition (4.2) and explaining the basic disagreements with Kuhn and Lakatos (4.3), I present here a fragment (from Apollonius over Hipparchus to Ptolemaeus) of the history of geocentric astronomy. This example will be used in 4.2 and 4.3. to illustrate Laudan's definitions and claims.

The ontology on which these three astronomers build 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 laws:

(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 laws requires determining the values of the two radii and of the two angular speeds of motion. A good implementation of Apollonius' paradigm 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.

4.2 Research traditions: definition

The working definition which Laudan proposes in his 1977 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. (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)

Our example in 4.1 illustrates this. At the first stage, we have a paradigm (indeed, the successive stages of a research tradition are paradigms as defined in section 2) that is characterized by the ontological claims G_A and G_B and by the methodological rule that astronomical theories must be constructed by applying G_1-G_6. If we compare this with the second stage, the methodology has changed a bit (G_5' and G_6' instead of G_5 and G_6), but the ontology remains the same. The same holds for the transition from Hipparchus to Ptolemaeus. So we have a research tradition in which the ontology remains the same, but the methodology evolves. For an example of a research tradition in which the ontology changes too, see section 6 (Bohr and his successors).

4.3 Not all paradigm shifts are revolutions

According to Laudan, there are two kinds of change within a research tradition. One type is the one emphasised by Lakatos: the auxiliary hypotheses in the theories which are developed in the tradition, can change. For instance, it can take astronomers working with the Apollonian paradigm some time to find the optimal radii and angular speeds. Changes of the second type are more fundamental: (at least) one of the core assumptions of the paradigm is given up. In some cases, like in our example, the changes are small. In other cases, such as Newton, the change is big. Then we have a revolution. The upshot is that not all paradigm shifts are revolutionary: Kuhn's thesis K_3 is not correct.

5. Are revolutions important?

5.1 The problem

Are revolutions important for the growth of science? Kuhn's answer is positive: without revolutions scientific belief revision (as opposed to mere addition of beliefs by puzzle solving) is impossible. However, this conclusion rests on thesis K_3, which is wrong. In Lakatos' view, belief revision is possible without revolutions: old solutions for puzzles are replaced with new ones. But without revolutions, in which a new research program with its characteristic hard core arises, scientific evolution would be very limited. In Laudan's model, which is the most accurate one, revolutions seem superfluous: since no part of the ontology or methodology is immune, it looks as if science only needs the gradual changes that are typical for the evolution within research traditions. In section 5.2-5.5 I will show that revolutions are necessary: certain types of changes in the ontology of a paradigm entail changes in other parts of the paradigm. In those cases, we have only two choices: leave the ontology as it is or provoke a revolution. Small changes are impossible.

5.2 Specifying the ontology of a paradigm

Ontologies as I conceive them can contain claims of five types:
(1) Claims about *kind* links between *concepts* (or negations of such claims). Examples are:

> Black is a kind of colour.
> Yellow is kind of colour.
> A reptile is a kind of animal.
> A mammal is a kind of animal.
> A bird is a kind of animal.
> A canary is a kind of bird.
> A raven is a kind of bird.

Raven is not a kind of colour.
A bird is not a kind of mammal.

(2) Claims about *part* links between *concepts* (or their negation). Examples of such claims are

Birds have a beak.
Birds have wings.
Ravens have wings.

(3) Claims about *part* links between *particular objects* and *concepts* (or their negation). Examples of such claims are:

John has legs.
John has a heart.
John has no wings.

(4) Claims about *part* links between *particular objects* (or their negation). Examples of such claims are:

Flanders is a part of Belgium.
Belgium is not a part of France.
England is part of the United Kingdom.

(5) Claims about *instance* links between *particular objects* and *concepts* (or their negation). Examples of such claims are:

Tweety is a bird.
Tweety is a canary.

This characterization of ontologies is inspired by Thagard 1992 (especially Chapter 2). He writes:

> 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. (pp. 32-33; italics in original)

Thagard suggests here that ontologies can be specified in terms of kind and part links. I think he is right, with two qualifications:
(a) Thagard has in mind only part links of type (2). He does not take into account types (3) and (4). Such part links occur in the ontology of paradigms in domains where the relevant objects have names and are limited in number (e.g. astronomy).
(b) In those domains, the ontology often contains instance links. This means that sometimes instance links are as fundamental as part and kind links.

5.3 Extensions of an ontology

If a new ontology is formulated, it may happen that links are added but *no links are deleted*. 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 consists 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 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.

5.4 Revisions of an ontology

If at least one link is deleted and replaced with another one, the ontology is *revised*, not merely extended. I 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 ontology) to another branch.

Similar things can happen with part links. In Stahl's Phlogiston Theory, a metals consist of calx and phlogiston; phlogiston and calxes are elements. According to Lavoisier, calxes consists 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 ontology 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 not revolutionary. The revolutionary changes are the ones in the instance links:

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

5.5 Revisions cause revolutions

Consider two paradigms A and B, where B replaces A. If the ontology of B is identical to or an extension of A, B can recuperate the explanatory apparatus of A. If the ontology of B is a revision of A, the explanatory apparatus of A cannot be recuperated, because the latter contradicts the new ontology. Let us look at some examples.

Hipparchus could recuperate the explanatory apparatus of Apollonius: he could use his system of deferents and epicycles (i.e. he could use the values of the radii and angular speeds of motion as calculated by Apollonius). The same for Ptolemaeus and the apparatus of Hipparchus: the latter could use the former's auxiliary hypotheses, including the ones about the positions of the eccentrics. This contrasts with Copernicus. He used epicycles and eccentrics, but had to formulate new hypotheses about the values of all the relevant variables (radii, angular speeds) because he had to construct circles around the Sun (or better, an eccentric near the

Sun) instead of circles around (an eccentric near) the Earth. He could not recuperate the old explanatory apparatus, though he used two of its tools. The reason for this difference is clear: the ontology of Apollonius, Hipparchus and Ptolemaeus is identical, while Copernicus has revised the ontology.

Aristotle used two principles of inertia: celestial bodies move in circles if no force is exerted on them, while terrestrial bodies move straightforwardly to their natural place if no force is exerted on them. Newton could not use these principles anymore, because of the collapse mentioned above: the distinction between celestial and terrestrial bodies is given up.

5.6 Conclusion

Unless we accept that revisions of ontologies are never necessary, revolutions are indispensable for scientific growth. Revisions of ontology cause a collapse of the explanatory apparatus. Therefore, they must be followed by drastic changes in the methodological part of the old paradigm. Revisions of ontology are impossible without provoking a revolution, so there are cases in which belief revision is necessarily radical.

Laudan does not have an operational criterion for distinguishing research traditions. We now can formulate one: if a new paradigm shares the ontology of the old one, or is an extension of it, they belong to the same research tradition. If the ontology of the new paradigm is a revision of the old ontology, the new paradigm is the start of new research tradition.

6. Rational pursuit

6.1 The problem

In Laudan's view, research traditions can be evaluated in two ways:

> We may, to begin with, ask about the (momentary) *adequacy* of a research tradition. We are essentially asking here how effective the *latest* theories within the research tradition are at solving problems.

> This, in turn requires us to determine the problem-solving effectiveness of those theories which presently constitute the research tradition (ignoring their predecessors). (1977, pp. 106-107)

If our problem is to choose which of two traditions to accept (for use in explanations and predictions) we have to choose the one with the highest problem-solving adequacy, as measured by the problem-solving effectiveness of the latest theories in each tradition.

Acceptance must be distinguished from pursuit. We may decide to pursue a research tradition (i.e. try to develop it further) even if its problem-solving adequacy is lower than its rival(s). According to Laudan, this pursuit can be rational:

> Putting the point generally, we can say that *it is always rational to pursue any research tradition which has a higher rate of progress than its rivals* (even if the former has a lower problem-solving effectiveness). (1977, p. 111; italics in original)

I agree with Laudan (against e.g. Kuhn) that rational choice is possible in the *context of acceptance*. However, his criterion for rational choice in the *context of pursuit* makes no sense. The rate of progress of a research tradition is not a reliable indicator of its intrinsic value, because this rate is determined by at least two other factors, viz. the number of researchers that have worked in it and the average quality of these researchers. Applying Laudan's criterion for allocation decisions would result in well-funded research groups getting more and more money all the time: their tradition has a high rate of progress because they can employ a lot of researchers. I do not want to deny that the intrinsic quality of a tradition is one of the determinants of its rate of progress. However, the rate of progress is a bad way of measuring this intrinsic quality, because it is determined by many other factors.

Laudan's failure does not entail that rational pursuit decisions are impossible. In sections 6.2 and 6.3 I will argue that they are often possible at a different level, viz. *within* research traditions rather than *across* research traditions.

6.2 Two criteria for rational pursuit

Can it be rational to pursue one line of research rather than another one?

In principle, the answer is positive. Two criteria can be formulated.

(C_1) If the toolbox of paradigm B is an extension of the toolbox of paradigm A, B must be preferred to A.

(C_2) If the toolbox of paradigm B can be extended so that it contains the toolbox of A, and the current problem solving power of B is larger than that of A, B must be preferred to A.

If A and B belong to the same research tradition, one of these criteria is often applicable. Therefore, pursuit decisions *within a research tradition* are often rational. In 6.3 I provide examples of such decisions.

6.3 Pursuit decisions within research traditions

Let A be the paradigm of Hipparchus, B that of Apollonius. The toolbox of B is an extension of the toolbox of A: both contain epicyclic motion, while the latter does not contain the eccentric motion. The case of Ptolemaeus versus Hipparchus (equant as additional tool) is similar. In each case, criterion C_1 is applicable.

Copernicus considered the fact that he could do without the equant, one of the most important advantages of his heliocentric system. The observations of Tycho Brahe, which were approximately twenty times as accurate as Copernicus' data, showed that the original Copernican system could not accurately predict planetary motions. Johannes Kepler tried to improve the heliocentric system in various ways, e.g. by adding more epicycles and by re-introducing the equant. All this did not work. Kepler's solution is well known: he introduced *elliptical orbits* and threw away three classical tools. This was a rational decision because criterion C_2 is applicable. Kepler's paradigm does not include the whole toolbox of Copernicus, but its problem-solving effectiveness was higher at Kepler's time and it could have been extended in such way that the three classical tools are re-introduced. Such reintroduction did not occur because it was superfluous, but was nevertheless possible:
(1) One can re-introduce epicycles, which results in elliptical deferents instead of elliptical orbits.
(2) One can re-introduce eccentrics, which would mean that the Sun (contrary to what Kepler claims) is not located at one of the foci of the

elliptical orbit of each planet.
(3) One can re-introduce the equant, which would mean that the regularity in Kepler's law of equal areas is changed: the areas should be defined with respect to the equant point, instead of the Sun.

6.4 Conclusions

Rational pursuit within a research tradition is often possible. If A and B do not belong to the same research tradition, the criteria C_1 and C_2 usually do not apply. The result is that, in most domains, the number of rationally pursuable paradigms is limited (only one in each research tradition) but larger than one (because several incommensurable research traditions exist).

7. Revolutions and creativity

7.1 The problem

Let us define a *crisis* as a situation in which the adherents of a paradigm are convinced that some (but not necessarily all) cognitive problems in its domain cannot be adequately solved by means of of its constraints. In other words, they are convinced that a paradigm shift is necessary. This paradigm shift can be revolutionary (radical) or non-revolutionary (gradual). And it can be creative or non-creative. A paradigm shift is non-creative if and only the new paradigm contains only variations (e.g. negations, weakenings, strengthenings, analogies) of old constraints. A paradigm shift is creative if and only if the new paradigm has constraints that are no variations of old ones. It is tempting to assume that revolutionary changes are always creative (in the sense just defined) and vice versa. In 7.2 I present examples that support these hypotheses, while in 7.3 I discuss some counterexamples.

7.2 Confirming cases

The planetary model of Apollonius was the successor of the concentric spheres paradigm. According to the adherents of this paradigm (e.g. Eudoxus and Aristotle) the Stellar Sphere contains a number of concentric transparent spheres (26 in the case of Eudoxus, 55 in the case of Aristotle). The outermost of these transparent spheres rotates around an axis embedded in the Stellar Sphere. The next sphere rotates around an axis embedded in the first sphere, and so on. All planets are fixed on the surface of one of the transparent spheres, but not all spheres contain a planet. If we compare this with Apollonius, we see a revision of ontology: the transparent spheres are gone. So Apollonius' paradigm was revolutionary. It was also creative: there is no trace of deferents and epicycles in the old paradigm.

The introduction of the eccentric by Hipparchus is non-revolutionary (small change, identical ontology) and non-creative. The latter becomes clear if we realise that G_5 (cfr. Section 4.1) is equivalent to the conjunction of two claims:
(a) For each planet there is a point E, which is the centre of its deferent
(b) This centre is always the Earth.
In G_5', Hipparchus simply retains (a) and rejects (b).

The introduction of the equant by Ptolemaeus was not creative either. The second half of G_6' is retained. The first half of G_6' is simply negated: while Hipparchus assumes that E (the point with respect to which the motion of D, the centre of the epicycle, is circular), and Q (the point with respect to which the motion of D is uniform) coincide. Ptolemaeus rejects this identification.

7.3 Counterexamples

An obvious counterexample to the claim that all revolutions are creative, is Copernicus. His two most important innovations were:

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

These claims are revolutionary (revision of ontology, collapse of explanatory apparatus), but are simple negations of claims of the old paradigm. His two less dramatic innovations were:

The Moon is a satellite.
The Universe contains satellites.

These claims are not revolutionary (extension of ontology), and the motion of satellites is circular.

Kepler is a counterexample to the other direction of the equivalence: his introduction of elliptical orbits was creative, but not revolutionary (because he left the ontology intact).

8. Summary

Our results can be summarised as follows:
(1) Revolutions are indispensable for scientific growth, because revision of ontology is impossible without provoking a revolution.
(2) Rational pursuit within a research tradition is often possible. In most domains, the number of rationally pursuable paradigms is limited but larger than one.
(3) The hypothesis that revolutionary changes are always creative and vice versa, cannot be maintained: there are counterexamples to both directions of this equivalence.

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