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INTERROGATIVE REASONING AND DISCOVERY: A NEW PERSPECTIVE ON KEPLER'S INQUIRY

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1. Introduction

In recent years, serious study of scientific discovery has begun to flourish again. Although the discussion has cleared up some issues, the field still is in need of a new kind of systematic approach. Such an approach should locate and justify the epistemic role of discovery within a larger theory of scientific practice, and its basic claims should receive support from historical and contemporary reports of actual scientific practice.

Few proposals have even tried to realize these desiderata. Historical case studies do not usually address the systematic goals, while systematic studies are too abstract and idealized to accommodate the details of historical studies. Thus, models which attempt to mediate between these poles are needed. In this paper, I shall introduce a model which accords fairly well with the desiderata. Its conceptual core is the interrogative model of inquiry (I-Model, for short) which Jaakko Hintikka and his associates have been developing in recent years. I shall argue that the I-model offers a promising theory of scientific inquiry, and, in particular, that it can bring light to the structure of reasoning employed by working scientists. The main argument for this goes as follows. The model is founded on a precise logical theory. As a logical model of knowledge acquisition it can offer us something that the historical case studies of scientific discoveries have not offered: a *logic* of scientific discovery. On the other hand, I-model´s account of the discovery process is less idealized than in previous systematic models of discovery. It thus captures more details of historical episodes. Consequently, the I-model forms a kind of synthesis between historical case studies and previous accounts of scientific discovery.

Further support for the I-model of discovery is obtained by considering excerpts from one important example: Kepler´s reasoning which led to the discovery of the elliptical orbit for Mars. This example is prominent since historians of science have paid much attention to Kepler´s inquiry in *Astronomia Nova* (1609), and there also have been several philosophical accounts of Kepler's work.

2. The I-Model of Discovery

2.1. Interrogative derivations

According to the I-model, scientific discoveries can be viewed as answers to the inquirer´s theoretical and practical questions. The fundamental ingredients of the I-model are *interrogative derivations* which are logical reconstructions of the question-answering process. They consist of interrogative and deductive moves applied to a set of sentences (i.e. the initial premises and the seeked conclusion). The knowledge-seeking inquirer is thought to construct these arguments. By performing interrogative moves the inquirer can ask questions from an outside source of information (an oracle). If an answer is forthcoming it can be added to the premises of inquiry. Deductive moves are just like usual natural deduction rules with some minor differences (see, for instance, Hintikka 1989, Hintikka & Bachman 1991).

In principle, the interrogative derivations can be formulated in any precise formal language for which a proof procedure can be specified. This formal language can be ordinary first-order logic or, in more extensive applications, a fragment of epistemic logic which is called the logic of knowledge statements. It is not possible to go into the details here (see Maunu 1993, Hintikka, Halonen & Mutanen 1996), but in general it depends on the application what language and how much logical details are needed. In some cases a simple first-order version of the I-model is enough, in other cases we need a more detailed formalization and more powerful tools.

In the basic version, the inquirer tries to establish some given conclusion or seeks answers to some question by construing its interrogative derivation from a set of premises T. The logical details of the interrogative derivations can be captured by using a variant of Beth´s method of semantical *tableaux* (in the first-order case) or sequent calculus rules (which provide an alternative proof procedure for the logic of knowledge statements, see Hintikka *et al.*, 1996). Sometimes, especially when the explicit formalization would require too much tiresome details, we prefer more informal interrogative arguments (as in my treatment of Kepler below). But in these cases too, the same deductive and interrogative principles are used. The initial premises T codify the background knowledge or a theory which the inquirer assumes to be true or at least established to some extent in the beginning of the inquiry. Hence, the initial premises represent an inquirer´s epistemic situation, the knowledge which bear on the selection of questions as well as on the process of finding solutions (see below Section 3).

Now we can see in what sense we can speak about a *logic* of discovery here. In a sense, interrogative arguments generalize the common picture of logical deduction. The feature which distinguishes the I-model from the ordinary logical models is that in construing interrogative arguments *the inquirer can acquire further information during the process.* The result is a model of scientific inquiry in which the scientist addresses questions to some outside source and uses the answers as well as relevant background knowledge to infer new laws or to explain facts and low-level generalizations. This picture of inquiry is intuitively appealing: it corresponds closely to our image of scientists at work, and, furthermore, to their self-image too.

To complement this basic picture, we need two important divisions. One is between *definitory* and *strategic* rules (see Hintikka 1989). Definitory rules tell the inquirer which moves are acceptable in a given situation while strategic rules restrict further these acceptable moves by telling which of them are the most profitable ones given the goal of the inquiry. The former specify the deductive and interrogative moves which are allowed, and therefore define what interrogative derivations are, the latter are analogous to methodological and heuristic rules. By focusing on strategic rules, we can incorporate many methods of science into interrogative reasoning.

Another important distinction is between "big" principal questions and "small" operational questions. The former determine the general goal of inquiry while the latter function as tools in this process. The distinction results in a hierarchical structure of inquiry in which the general goal, the solution to the principal question, is achieved by means of an array of micro-inquiries which seek solutions to the more restricted operational questions.

2.2. Discovery and justification

One consequence of this approach is that there is no clear and principled distinction between discovery and justification. Since they both consist of logical reasoning and queries for further information, a discovery process can be intermingled with justificatory arguments, and *vice versa*. It can be argued that the same definitory rules operate in the construction of both discovery and justificatory arguments, and that the main contrast between them comes from strategic considerations (see Hintikka 1987). For instance, an appropriate strategy of justification is to select questions in a way which maximizes the reliability of potential replies while the goal of discovery process is to achieve new results. It is safe to assume that the strategies of discovery are based on a bolder selection and pursuance of questions than the strategies of justification.

Another consequence of our approach is that the validity of a traditional objection which denied the existence of a logic of discovery can be reconsidered. It can be argued that its negative conclusion is avoided if we make a distinction between logic in a sense of abstract calculus and general methods of discovery. The philosophers who denied the possibility of a logic of discovery meant only general methods of discovery, not logic in a sense of calculus. If this misunderstanding is corrected, we can see that there can be a logic of discovery which is based on the definitory rules of the I-model ("proof-theory"), and on strategic rules which are more or less restricted local strategies ("heuristic methods"). In other words, the principles by which interrogative arguments are constructed specify an abstract proof calculus, and insofar as these arguments are used for reconstructing the knowledge acquisition or discovery process, we can speak about a logic of discovery. However, in addition we need extra-logical principles, strategic rules, which put constraints on acceptable arguments. These rules may vary from case to case, depending on the contextual features of the application that we (as kind of meta-inquirers) are focusing on.

2.3. A historical remark

For logical empiricists the logic of science was based on the first-order predicate logic as presented in Russell's and Whitehead's *Principia Mathematica* (see Brown 1977, Part I). Their program lead to many problems which were due to the limitations in the expressive power of the first-order logic (i.e. the truth conditions of material implication) and which, from the point of view of later, more practice-oriented philosophy of science, are merely artificial pseudo problems, totally alienated from the actual practice of science. The logical picture of discovery offered by the I-model is, in a sense, continuation and extension of the logical empiricists´ original program. This time, however, we can avoid the pitfalls of too abstract approaches and incorporate enough local historical features into our model.

3. Strategies of Discovery and Historical Studies

3.1. Strategic perspective on inquiry

Although the I-model is a logical model of knowledge acquisition, it still leaves room for the pragmatic factors. The strategic perspective makes it possible to incorporate theories and methods from the context of inquiry into the logical reconstruction. There already have been many attempts to develop a strategy-oriented approach such as the AI-based, computational models of discovery (see Langley *et al.* 1987, Darden 1991). By the strategic approach, the inquirer´s reasoning in all junctures can be elegantly reconstructed. We can explicate how the inquirer chooses the relevant questions, what answers she considers to be acceptable and how she assess them, what are his methods of finding answers, and so on.

In short, the strategies of discovery are rules which describe complete or partial plans of action,[1] and which can be used to reconstruct the inquirer´s reasoning during the discovery process. It should be

[1] The term "action" should be interpreted broadly here. Besides more concrete acts it can include, for instance, such cognitive acts as inferences.

noticed, however, that the question whether these strategies are actually used by the inquirers is left open. I only claim that they give us information about the possible ways that the historical agents may have proceeded in their problem situations. Strategic rules are tools of rational reconstruction, but they are good tools which enable us to make fairly realistic reconstructions (cf. Darden 1991 which have many similarities with my approach).

The general/local-dimension is a natural way to classify strategies. General strategies apply to situations which fulfill certain formal or procedural characteristics, while local ones depend on specific, contextual features. General strategies are also sometimes called weak methods (see Langley *et al.* 1987). Although general, the exclusion of a context means that they are not necessarily very efficient. On the other hand, local strategies are associated with strong methods since they depend on domain-specific constraints and, therefore, are usually efficient.

It is clear that generality comes in degrees. The location of a strategy in this dimension is measured by its invariance over various possible states of nature. General strategies do not depend on particular states of nature. In contrast to this, a pure local strategy could be applied only in some particular situation. Between these poles remains probably the majority of cases, although it is difficult to specify any strict ordering.

In the philosophical and scientific literature, there are several sources in which discussions of various strategies of inquiry can be found. One interesting possibility is to consider interrogative strategies which are analogous to the deductive strategies in the first-order logic (Harris 1990). Another possibility is to interpret various general methodological rules as strategies of inquiry in our sense.[2] Third, AI theorists have examined some general problem-solving heuristics. They may be useful for our purposes, too. Fourth, there are a few interesting and relevant

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[2] These include, at least, the method of analysis and synthesis, analogical inferences, symmetry considerations, the correspondence principle etc. I do not discuss these familiar methods in this occasion, but see Hintikka & Remes (1974), for the method of analysis; Hesse (1974), Chap. 11, for analogy; Weyl (1952), van Fraassen (1989), for symmetry; and Post (1971), Pearce & Rantala (1983), for the correspondence principle. One interesting strategic method involves the use of thought-experiments as a means to illustrate the features of counterfactual or highly idealized situations. For an interesting account of thought-experiments, see Brown (1991).

accounts of mathematical heuristics (e.g., Poincaré, Hadamard, Polya, Lakatos). It also is appropriate to distinguish the strategies which pertain to the structure of interrogative arguments from those which pertain to the initial choice of questions or other objectives of inquiry.

3.2. On the origin of questions

Let me now elaborate a bit on the problem of question selection. The problem is to say what strategic considerations help the inquirer to select the questions she should pursue. The inquirer who tries to answer a question does not work in a vacuum. A store of available background knowledge determines at least partly what questions are important and what are plausible answers. This store contains diverse material from many sources. In case of scientific inquiry, the most important source is without doubt the current theoretical and practical knowledge of the field in question. But it is possible that other factors affect the inquirer´s decisions. The role of such external factors as economical and political circumstances is controversial, but at least in some cases they have been important. Hence the problem is to say how the questions arise from the background knowledge and how the most important ones are identified.

We can assume that gaps or anomalies in background knowledge generate questions, and, consequently, the main challenge is to show how the inquirers identify them, and choose the ones that are worthy of pursuit. The central notion here is the presupposition of a question. It represents knowledge which must be established as true before the question can even be reasonably asked. This demand guarantees that there is some hope to receive correct answers. It is evident that items of background knowledge can function as presuppositions of questions.

It is not possible for the inquirer to query everything that is left open in her background knowledge. Random querying would be an inefficient strategy. Some further principles on question selection must be imposed if one wants to make the interrogative process more effective. I think that the solution lies in a structured notion of background knowledge which also attaches certain epistemic utilities to questions and answers. This solution was originally proposed by Matti Sintonen (1984, 1985, 1989). He used the so called structuralist theory-notion in the explication of an inquirer´s theoretical, axiological, and heuristic background.[3]

In the structuralist approach, theories or larger theoretical frameworks are represented as theory-nets. A theory-net is a set of theory-elements which is structured by a specialization relation obtaining between elements.[4] Formally a theory-net is a partially ordered set whose knots are theory-elements and whose cords represent the specialization relation (Balzer *et al.*1987, p. 172). In addition, theory-nets may contain information about the inquirer´s values, mathematical and experimental techniques etc. This, of course, presupposes that the inquirer somehow holds the theory-net and intends to apply it.

However, I think that we should not pay too much attention to the details of the structuralist philosophy of science here. It is enough, for our purposes, to assume that the inquirer´s store of background knowledge can be represented by some kind of hierarchical structure where the position in the structure tells something of the epistemic weight attached to the item. I shall call these representations *diagrams* or *theory-diagrams*.[5] Diagrams consist of sets of nodes which represent the items of background knowledge. Vertices between nodes represent the relations between the items of background knowledge.

It is easy to see how the diagrammatic representation provides ways to find relevant theoretical and practical presuppositions (see Sintonen 1984, 1989, 1996). It helps (i) to define the identity of problems, (ii) to select the important questions, and (iii) to find answers to questions. Furthermore, questions arise because there are gaps in a diagram T. In a typical case, these gaps involve uncertainty about whether T can provide an explanation of some intended application or whether some conceptual or empirical anomaly can be resolved. An answer may demand an expansion of T by some new items t, t´,..., or it may demand that some items o, o´,... are deleted and replaced by some new items n,

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[3] For an account of structuralist philosophy of science, see Stegmuller (1979), Balzer *et al.* (1987).

[4] Theory-elements, in, turn are more limited units of a theory-structure. They contain, for instance, laws and descriptions of intended applications.

[5] In the present study, however, I shall usually refer only to the inquirer´s background knowledge or background information, for the exact structure of it is in many times either not important or too inconvenient to specify in detail.

n´,.... In accordance with (iii), T also provides tools to answer these questions by putting constraints on acceptable answers.

In the selection of questions, the inquirer´s values as codified into epistemic utilities are important. The questions which are answerable by the existing evidence are not necessarily the ones that are worthy of pursuit. Additional conditions are still needed. One plausible strategy is to select the questions whose answering maximizes (or satisfices) the epistemic and practical utilities of the inquirer. These utilities can motivate the pursuance of questions by balancing the epistemic gains with practical costs.

4. A Reconstruction of Kepler´s Inquiry

4.1. A new perspective on Kepler

Further support for the I-model of discovery comes from historical examples. There already are studies of Newton (Hintikka & Garrison, see Garrison 1988) and Darwin (Sintonen 1990) in which the I-model is successfully applied. I shall briefly outline the interrogative account of Kepler´s inquiry in *Astronomia Nova*. It shows how Kepler´s inquiry can be viewed as an interplay between queries put to the source of observation (i.e. Tycho Brahe´s stock of observations) and deductive moves (i.e. complex mathematical calculations). It also shows how this interplay was guided by strategic considerations, employing both specific astronomical methods and more general methodological principles. In this way we can obtain a fairly realistic logical model of Kepler´s inquiry.

Historians of science have paid much attention to Kepler´s reasoning in *Astronomia Nova* (1609), the book in which the discovery process of the first two of the famous three laws of planetary motion is described.[6]

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[6] See Aiton (1969), Wilson (1968), (1972). For a more through presentation of Kepler´s background as well as his reasoning in *Astronomia Nova*, see Koyré (1973), Krafft (1991), Stephenson (1987), Kozhamthadam (1994). An english translation of *Astronomia Nova* is currently available as Kepler (1992). In the sequel, I shall use the shorthand AN for this book.

There also are several philosophical interpretations of Kepler´s work.[7] Philosophers have usually tried to reconstruct the discovery process in accordance with some metatheoretical mould which, unfortunately, have often led to too simple models. For instance, N. R. Hanson (1958) maintained that Tycho Brahe´s careful observations about Mars formed the only evidence from which Kepler began to work. This has been the standard view among the empiricist interpretations of Kepler´s work. However, it is based on serious misreading of Kepler´s writings. The proper appreciation of Kepler´s inquiry demands that we pay attention to his background. It was the astronomical tradition of his time together with Tycho´s observations that was the real impetus of Kepler´s work.[8]

4.2. The background and aim of Kepler´s inquiry

In this section, I shall outline the general features of Kepler´s inquiry in AN, and show how they can be captured by the I-model. Our theory of discovery was cast in epistemic and erotetic terms. In order to find out whether these notions apply to historical cases, the real issue is not whether they were explicitly used in a historical episode, but whether it is possible to build a model of discovery which adequately reconstructs the actual reasoning. So, our task is to examine what was included in Kepler´s background knowledge, and how he chose from it the questions which he decided to pursue, and how the answers in their turn changed the background knowledge and the goals of the inquiry.

A critical evaluation of Ptolemy´s, Copernicus´, and Tycho´s planetary models were Kepler´s points of departure. He was able to transform many of their methods and problems and reach genuinely new insights. In his own words, he was moving from the "imitation of Ancients" towards "New Astronomy". A good example is the importance ascribed to physical considerations. On Kepler´s hands, mathematical

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[7] The important contemporary contributions to this discussion are Hanson (1958), Kleiner (1983), Lugg (1985), and Kozhamthadam (1994). There are also many earlier contributions, for instance, in the methodological writings of Mill, Whewell, and Peirce. See Wilson (1974).

[8] It is a curious fact that Hanson stresses this same point in his description of Kepler´s reasoning but fails to notice this in his more philosophical account of Kepler´s logic of discovery.

astronomy was not only celestial kinematics grounded upon purely geometrical hypotheses, it also was celestial dynamics which tried to discover the physical causes of celestial phenomena. He thought that celestial bodies were subjects to forces in the same way as sublunar bodies were. Physical considerations gave him valuable strategic and heuristic material which directed the invention and justification of geometrical constructions and models.

Let us now proceed to the description of Kepler´s inquiry from the I-model´s point of view. The general aim is to find out what the central background assumptions (i.e. the epistemic context) were and how they were filtered into more refined research questions.[9] I am not able to give detailed answers to all of these questions here. Although Kepler´s own description in AN is detailed and, with some reservations, a reliable guide to the actual inquiry,[10] the account below is selective. I concentrate on a small but, I hope, representative subset of his questions. However, there is also a brief and simplified narrative of the whole inquiry, which makes my account more readable for the non-specialists. Still many concepts are explained only sketchily, and many intricate details are ignored. For a fuller discussion of Kepler´s concepts and problems, I refer to the excellent historical treatises listed above as well as to Kepler´s original text.

Kepler´s initial situation and the aim of his inquiry are nicely described in Lugg (1985). Although I do not agree with everything Lugg writes, he nevertheless characterizes the general situation well. He writes (*ibid.*, p. 211-212):

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[9] The most extensive discussion of Kepler´s epistemic background is Kozhamthadam (1994). He divides the background into religious, philosophical, and scientific components, and examines step by step how these components direct Kepler´s decisions. Although he seems to exaggerate the role of religious beliefs, Kozhamthadam´s account is very interesting from our point of view, too.

[10] It is often claimed that scientists´ own descriptions of their discoveries are not confident guides to actual episodes. The discoverers may try to rationalize the actual process in order to convince their colleagues of the value of a discovery. The same tendency is also visible in Kepler´s case. In AN, however, the few afterwards made additions to the description of original course of inquiry can relatively easily be identified and eliminated. These kind of attempts occur, for instance, in the detailed commentaries of Koyré (1973) and Stephenson (1987).

> To understand Kepler´s discovery, we need to see him as having struggled not with a single problem (namely, to determine the orbit of Mars) but with a series of problems (namely, to determine the "free parameters" of various models of planetary motion). When Kepler began his investigations, he believed that he knew that the orbit of Mars was circular; what he did not know and wanted to determine using Tycho´s data were the relative positions of the Sun, Mars and the equant point. It was while investigating this problem that....he began to realize that he might have to modify the "astronomical tradition into which he was born."....[H]e used the data in conjunction with theoretical and methodological considerations to revise and refine existing scientific theory.

What is interesting in this passage is the idea that Kepler was struggling, not with a single problem, but with a series of problems. He started with one principal problem, namely that of determining the orbit of Mars using Tycho´s relatively reliable and accurate data. But he soon realized that the task was more complicated. In order to achieve his goal, he had to solve several difficult problems. These problems constitute the several battles of his war on Mars. From the point of view of the I-model, these battles form an array of micro-inquiries, each aiming to answer some operational question.

The general goal, which could be described as an attempt to find an acceptable answer to the principal question, remained relatively constant during the long inquiry. The permanent aim was to construct an adequate planetary model for Mars from which the positions of the planet could be calculated. On the other hand, the initial premises changed radically during the inquiry. The ellipse law and the area law were in fact part of the premises, not the desired results.[11] These changes and revisions also changed the picture of the adequate planetary model of Mars. At the initial situation, it was based on the circular orbits and the principal question was to determine the relative positions of the Sun, Mars and the equant point. Near the end of the inquiry, the planetary model was based on the elliptical orbits and the principal question was to determine the values of the parameters of this model (e.g., the location of the Sun, its

[11] Kepler´s own views of elliptical orbits were ambivalent. Although he thought that the determination of the true planetary orbits was an important achievement, he also held that their elliptical shape was an anomaly in the general structure of the universe.

compatibility with physical assumptions). We can then say that the goal was all the time to reach a model of Mars but the content of this desired model changed during the inquiry.

Kepler´s initial situation could be characterized as follows:[12]

Premises	Conclusion
T : The orbit of Mars is a circle. The velocity of Mars is regular with respect to the equant point.	The relative positions of Mars, the Sun, and the equant point are x, y, z.

Let us now study Kepler´s interrogative path to discovery in more detail. To begin with, Tycho Brahe´s careful observations formed the necessary background. They were Kepler´s main source of empirical answers, and were, furthermore, thought to be accurate within the limits of observational error (about 2´). Consequently, when he confronted problems, the geometrical and physical premises, not observations, were in doubt. These prior assumptions were revised by putting ingenious questions to the source of answers (i.e. Tycho´s stock of observations). In the process, the initial principal question was reduced to arrays of

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[12] Notice that the conclusion on the right column says that Kepler knew that there was some constant positions to be found but did not know what the exact values for them were. He has to fix the open parameters in the model. Compare with the following passage from Whewell´s *History of the Inductive Sciences* (1875), p. 291: "In the first place, we may observe that the leading thought which suggested and animated all Kepler´s attempts was true, and we may add, sagacious and philosophical; namely, that there must be *some* numerical and geometrical relations among the times, distances, and velocities of the revolving bodies of the solar system. This settled and constant conviction of an important truth regulated all the conjectures, apparently so capricious and fanciful, which he made and examined, respecting particular relations in the system." (Italics in original.)

operative questions which took singular observations as answers.[13] This reduction was often made by help of complex mathematical calculations which involved the then available trigonometrical and geometrical methods. Sometimes the task was accomplished by pure metaphysical speculation, as we shall see below.

Originally, Kepler´s desire was to use Tycho´s observations to confirm his theory about the structure of the universe which he presented in his first book *Mysterium Cosmographicum* (1596).[14] In 1600 he came to Prague where Tycho Brahe was appointed as an imperial astronomer. At first Tycho was rather reluctant to give his observations to Kepler. This and other reasons led to serious conflicts between the two. However, Tycho died in 1601 and Kepler was nominated to be his successor. His commission was to accomplish the new planetary tables using Tycho´s observations. Now he could concentrate on the task of finding the proper orbit of Mars, the task he was already working on when Tycho was alive.

However, the task turned out to be far more difficult than anybody could have imagined. It took Kepler four or five years (ca. 1600-1605) to complete the inquiry. As a result, he could justifiably claim that the orbit of Mars is an ellipse. Besides this Kepler introduced several other important results, such as the method of areas, now known as Kepler´s second law, which improved or even revolutionized the methods and basic assumptions of mathematical astronomy. But as we shall see, there also were many other, albeit less well-known, results.

4.3. The vicarious hypothesis

In the first two parts of AN, Kepler made two remarkable improvements on the theoretical assumptions of mathematical astronomy. First, he argued that the distances and the positions of the planets should be read from the physical body of the sun, not from the mean sun which is the

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[13] Note that the principal question of an inquiry may be an operational question in the upper-level inquiry. This is related to the hierarchical picture of inquiry prevalent in the I-model. It corresponds to a method by which general questions are reduced to an array of more specific questions for which it is easier to find an answer.

[14] Kepler´s own biographical account is given in Chapter 7 of AN, see Kepler (1992: 183-7).

center of the earth´s orbit in Copernicus´ system.[15] Second, he proved that the plane of Mars and the other planets have constant inclinations with the ecliptic (the plane of the sun and the earth). In Copernicus´ system the planes of the planets are vibrating around the ecliptic.

Furthermore, Kepler showed that the planes of the planets have one common point, namely the true sun (i.e. the physical body of the sun). This seems to confirm his physical speculations which concerned the role of the sun as a mover of the planets. He was also skeptical towards empty points in space which do not have any physical interpretation. The acceptance of these points in the earlier models was due to the fictionalist interpretation of geometrical constructs. Kepler abandoned this view and contended instead that the constructs of astronomical models should be interpreted realistically.

A scientist´s background knowledge usually includes earlier theories and models as well as additional knowledge which is needed to apply the theories or models to particular cases. Kepler was not an exception. The first two parts of AN contain material whose purpose is to clear up the relations between Ptolemy´s, Copernicus´, and Tycho´s planetary models. These models, from which Kepler´s initial premises were selected, account for the irregular movements of the planets. Kepler´s own innovations are based on the methods and assumptions contained in these prior models.

The first model Kepler adheres to, the so called "vicarious" hypothesis, contains elements from the systems of Ptolemy and Copernicus: it is a heliocentric model in which certain elements are inherited from Ptolemy´s geocentric models. The most notable of these is a *punctum aequans* or an equant point. Equant points (the centers of equant circles) were introduced to describe irregular movements of the planets. An equant point is an off-centered point with respect to which the motion of a planet is regular (i.e. the planet´s angular velocity around the equant point is constant). It also was assumed that the sun (the earth in Ptolemy´s original theory) is not located in the center of the sphere. The distance between the center point and the sun (SC in Fig. 1) is the eccentricity of an orbit. In Ptolemy´s models for outer planets, the equant

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[15] For a detailed description of Kepler´s argument at this point, see Stephenson (1987), p. 31ff. The original arguments can be found from Kepler (1992), Chapters 5 and 6.

point and the earth are located symmetrically around the center point (the bisection of the eccentricity-principle):

S ———————	C ———————	E
(the sun)	(the center point)	(the equant point)

FIGURE 1

The inquiry which led to the vicarious hypothesis specified open parameters in the model. There are four such parameters: the eccentrities SC and CE, the direction of line of apsides (or the mean longitude of the perihelion) on which S, C and E lie, and the mean longitude of the planet. The most important open parameter was the position of the equant point (i.e. the eccentricity of the equant CE). The problem was whether this model also fulfills the bisection of the eccentricity condition, and if not, what is the exact location of the equant point? In this task, Tycho´s observations were of utmost importance. Kepler had in mind certain questions which he tried to answer by considering relevant observations. We can give the following reconstruction of Kepler´s questions:

(1) What is the location of the equant point?[16]

The correct answer to question (1) would have been sufficient to determine the positions of Mars, and, hence, to give the result which Kepler was looking for. However, the question was not an easy one to answer. In order to obtain an answer, (1) had to be reduced to a series of operational questions. This reduction was established by careful geometrical reasoning which involved four observations and some difficult proofs (see Koyré 1973: 173-5). The values of the parameters were determined by the iterative method which was based on the step by step correction of assumed values with respect to the known condition of correctness.

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[16] The line of apsides is the line which connects the points in the planet´s orbit which are nearest and furthest from the sun. The former is called perihelion, the latter aphelion. This line goes through the sun and the center point of an eccentric circle. It was assumed that the equant point is located on this line, as was depicted in figure 1 above.

The initial attempt to derive the parameters for the theory of Mars, the vicarious hypothesis, was only partially successful. Kepler soon realized that the hypothesis is false. The real eccentricity of Mars was smaller than was assumed, i.e. the center of Mars´ orbit was nearer to the sun than the vicarious hypothesis had put it. Kepler checked this by using Tycho´s observations of Mars near the perihelion and the aphelion. The results indicated that Kepler´s calculations were correct. Something was wrong with the theory. However, although the distances were wrong, the model gave acceptable heliocentric longitudes. Later in his inquiry, the longitudes calculated from the vicarious hypothesis functioned as a reliable source of answers which Kepler could use when he tried to answer questions which arise from the other models. This strategy also made it possible to compare the longitudes given by the vicarious hypothesis to the longitudes calculated from the other putative models, and in this way evaluate the latter's plausibility.

Subsequently, Kepler began to doubt the adequacy of one of his initial premises, namely the available theory of the earth. The earth had a special status among the planets in Copernicus´s models: its orbit was a simple circle on which the earth moved with regular velocity; the irregular movements of celestial bodies did not involve the earth. Kepler realized that this was wrong. The earth is one of the planets, and the same principles which govern the movements of the other planets must also apply to it. The development of astronomy needed a correct theory of the earth because the wrong positions ascribed to our home planet caused systematic errors to the planetary models.

Kepler used for this task a modified version of Tycho´s solar theory. To be more precise, he replaced the old theory of the earth by the model analogous to the vicarious hypothesis. Now the problem was again to determine the values of open parameters, such as the location of the equant point. This was done by an ingenious strategy, the so called triangulation method. The idea was to select three observations of Mars which were done after the periods of one Mars year (687 days). It is evident that Mars is then at the same place with respect to the sun, but the earth is at the three different places. In this way it was possible to construct triangles with the earth, Mars, and the sun at the corners, and by the trigonometrical calculation to determine the location of the equant point and the orbit of the earth.

At this stage, Kepler did not try to make the vicarious hypothesis better by the renewed theory of the earth. Instead, he began to doubt his premises even more. The assessment of different models and principles was done broadly according to methodological and mathematical standards that he adopted at the early stage of his career. As was mentioned above, the main tenet of Kepler´s methodological principles was the unification of astronomical and physical theories. Consequently, he lay much importance for the physical plausibility of different assumptions. Thus the equant point hypothesis was suspect because it was just an empty point in space without any physical meaning. Kepler thought that he must reveal the true physical causes of planetary motions. This meant that he had to raise completely new kinds of questions to get ahead in his inquiry.

4.4. Kepler´s physics and the distance law

Although Kepler adopted the heliocentric view, he was critical towards many details of Copernicus´s planetary models. One of these was the question of the mover of the planets. Copernicus assumed that planets move along solid circular spheres and each of them has a "soul", an intrinsic mover of a planet. The assumption of solid spheres was common in the astronomical tradition. It was part of Aristotle´s natural philosophy which in the late medieval was commonly thought to be a realistic description of the universe (see Grant 1991). By the late 16th century, however, the observations of comets had ruined the assumption of solid spheres, and the physical basis of astronomy was largely without foundation.

The physical part of AN is devoted to the study of forces which move the planets. The fundamental empirical observation was that the planets move swifter the nearer they are to the sun. Kepler had stressed this fact already in MC, and it formed the basis of his celestial physics. This led to the principle which is usually called Kepler´s distance law. According to the distance law, the speed of a planet around the sun is inversely proportional to its distance from the sun (note: not to the square of its distance). In fact, Kepler used the notion of delay instead of speed or velocity, since there was no useful concept of instantaneous velocity available.[17] In these terms, the distance law suggested the following principal why-question which Kepler tried to answer in the third part of AN:

(2) Why does the delay of the planets vary with their distance from the sun?

The earlier metaphysical speculations as well as the content of the distance law itself lead to the conclusion that there was some external force which moves the planets and which emanates from the sun. More accurately, Kepler came to this conclusion in two stages. First, he demonstrated (in chapter 32) that

> to the extent that a planet is farther from the point which is taken as the center of the world, it is less strongly urged to move about that point. It is therefore necessary that the cause of this weakening is either in the very body of the planet, in a motive force placed therein, or right at the supposed center of the world. (Kepler 1609/1992:376)

As we see, Kepler thought that the cause of weakening reside either (i) "in the very body of planet" or (ii) "right at the supposed center of the world". Now we come to stage two in which he used some metaphysical arguments to repudiate (i). Kepler concluded that the motive force is in the center of the system which, by his earlier results, is occupied by the sun. In this way the background knowledge helped to reduce (2) to the easier wh-question:

(3) What is the sun-centered motive force that moves the planets?

However, it was not easy to find exact answers to (3). The difficulties were caused by the fact that the planets do not travel smoothly along their supposedly circular orbits; they also librate around the orbit so that

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[17] The notion of delay (in Latin, *mora*) employed an important role in Kepler´s thinking. It referred to "the amount of time required for a planet to traverse some small arc in its orbit. Kepler said that a planet´s delays increased, rather than saying that its velocity decreased." (Stephenson, 1987:210). Thus, the concept of delay was almost inverse to the concept of velocity.

sometimes they are nearer, sometimes further away from the sun. The initial answer which Kepler examined could account only for the movements along the circle.[18] So it turned out that (3) have to be divided into two questions:

(4a) What is the sun-centered force that moves the planets along their circular orbits?

(4b) What is the force that makes the planets librate to and fro from the sun?

The presupposition of (4a) implies that if there was not any interrupting force, the planets would move along perfectly circular orbits with the sun at the center. Unfortunately, this is not how it happens so that there also are other forces queried by (4b). The *species immateriata*-hypothesis provided an answer to (4a). In order to find an acceptable answer to (4b), Kepler examined the most important alternatives his background knowledge suggested to him. Hence, the wh-question (4b) was further reduced to a propositional question. It was, then, still decombined into a couple of yes/no-questions:

(5a) Is the intrinsic animal soul of a planet responsible for the libration?

It must be noticed that Kepler´s concept of power or force differed from the ones in modern physical theories. It was a common assumption in those days that celestial bodies such as planets can have a soul which, in turn, is divided into three faculties, natural, animal and mental. This soul can have an effect on the movement of a planet. Hence every planet can act by the intrinsic animal force, *vis anima*. On the other hand, there are inanimate, natural forces such as magnetic and gravitational. These can radiate immaterially from their sources, analogously to the illumination of light. Kepler could answer (4a) by such inanimate forces, but (4b) resisted answers along these lines. Hence, it was understandable that

[18] The initial answer was based on the notion of invisible, immaterial field, *species immateriata*, which emanates from the sun in the same way as light. The sun revolves around its axis, the species revolves with it and carries the planets along their orbits.

Kepler sought the explanation from animate forces in accordance with (5a).

The answer to (5a) was negative. Animate forces were not realistic alternatives because this hypothesis would require too demanding skills to be ascribed to the planetary soul. The planetary mover should calculate the orbit by comparing its position with the sun´s position. Hence, it has to be more skillful than a mathematician trying to account for its orbit. Kepler found this conclusion unacceptable. He then tried to replace the hypothesis based on the forces of the animal faculty of a planetary soul, *vis anima*, with the hypothesis based on the forces of the inanimate, corporeal faculty of a planetary soul, *vis motrix*, which could account for libration but which do not require that the planet have a mind which is a skillful rational calculator. Thus, the other yes/no question was the following:

(5b) Is the inanimate faculty of a planetary soul responsible for the libration?

Kepler´s answer to (5b) was positive. In this point, he relied on the analogy between magnetic phenomena and celestial attractions, and especially *De magnete* (1600) by William Gilbert influenced his views (or confirmed his speculations). He thought that the *species immateriata* emanating from the sun consist of magnetic fibers, and, thus, that the sun is a magnetic body. Moreover, he thought that also the planets were magnetic bodies. He knew that the earth has magnetic poles, and so it was natural to generalize this property to the other celestial bodies.

The supposition that the planets have magnetic poles was important from the point of view of (5b). Kepler could explain the libration by supposing that a planet has two poles, one attracted by the sun, the other revolted by it. Depending on the angle of the corresponding pole towards the sun in different orbital positions, the planet was either attracted towards the sun or revolted away from it. In this way he could explain the deviation of the orbit from a regular circle. And moreover, he could explain it by postulating only such forces which did not required the hypothesis of animal soul (for details, see Stephenson 1987).

Kepler´s physical thinking was still essentially Aristotelean. He thought that a planet does not move at all if it is not actively moved by some force.[19] The lack of proper concept of inertial motion as well as another physical concepts was perhaps the main reason why Kepler did not reach adequate physical explanation of celestial motions. But if we keep an eye on his epistemic background, we notice that the questions he put up and the answers he supplied were not erroneous or irrational. Instead, they were a part of the carefully construed interrogative inquiry which could be rationally reconstructed as series of questions and inferences starting from the Kepler´s initial assumptions.

4.5. The area method

At the next stage Kepler tried to apply his physical results to the geometrical models, or in the terminology of the I-model, the physical results constrained the acceptable answers to the questions the geometrical models suggested. We notice how mathematical and physical principles interact epistemically: they put conditions on each other´s acceptability. The physical assumptions function as the conclusiveness conditions for acceptable answers.

The distance law was applied by the assumption that the time in which a celestial body travels some arc is directly proportional to the sum of distances between the sun and the arc. However, there were difficulties. In order to see this, we must consider in closer details Kepler´s conceptual background. In his time there was not any clear concept of instant velocity. Calculations were largely based on ratios between angles and line segments obtained from geometrical figures. As we noticed earlier, Kepler measured the velocity of a planet by its delay, i.e. by the time it takes a planet to travel some part of its orbit. It seemed natural to assume that the delay is proportional to the sum of the distances between the sun and the parts of the orbit. The poverty of mathematical background knowledge, however, prevented the calculation of the sum of distances.

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[19] Compare this to a later notion of inertial motion which ascribes to the physical bodies a property that they either stay in rest or move straightforward with constant velocity unless some force affects they motion. If this notion is adopted, the problem is to find a central force which keeps the planets in their orbits, not a force which pushes the planets along their circular orbits. The proper notions were developed only later by Descartes and Huygens.

In order to overcome the difficulties Kepler had to invent other methods. The proposed solution was the area method which emerged as a response to the difficulties in the calculations. The idea was to replace the sum of the distances with the area between the sun and the parts of orbit. The area included all the distances. By this method, it was possible to infer that radius vector draws like areas in like times. Hence, we can see here the origins of Kepler's second law (see also Aiton 1968). The distance law and the area method do not give equivalent results, and Kepler knew it. In spite of this he accepted the area method, since he probably thought that it could be used to approximate the sum of distances.

4.6. Oval-shaped orbit and the epicycle model

Next, Kepler tried to account for the orbit of Mars by using the Ptolemaic theory of epicycles. In this theory, the center of the epicycle moves around the sun on a circular path, the sun at its center point. The planet, then, moves along the circular path of another circle, the epicycle. He tried to apply the area method to this theory. The two, however, did not agree. It turned out that the results given by the area method demanded that Mars should move along the epicycle with a non-uniform velocity. Kepler was not happy with this result and he decided to check the longitudes in the apsides, quadrants and octants with the ones given by the vicarious hypothesis. He noticed agreement in the apsides and in the quadrants but an eight minute discrepancy in the octants.

After noticing this serious discrepancy between Tycho's observations and the calculations made by using the epicycle cum concentric circle hypothesis Kepler adopted the view that the orbit of Mars is oval (egg-shaped).[20] The oval curve is a shape which approximates the circle in the quadrants and observed errors in the octants. The important step was that he was now ready to abandon or at least doubt the initial premise that the planetary orbits are circles. We can present this step as a yes/no-

[20] Eight minute discrepancy was not serious according to the standards of previous astronomical tradition. Here the accuracy of Tycho's observations is crucial. Previous astronomist from Ptolemy to Copernicus used essentially the same data in which the size of errors could be around ten minutes of arc. Tycho's data contained only two to three minute errors.

question

(6) Is the orbit of Mars a circle?

The answer to (6) was negative and, hence, the negation of its presupposition has to be added to the background knowledge. The answer itself was found by the subinquiry which consisted of the array of operational questions, each querying the longitude of Mars in its various positions. As previously noticed, the approximately correct longitudes were calculated from the vicarious hypothesis. The answers obtained by this subinquiry also suggested a plausible revision of the initial premises, a revision which led to the abandonment of the circle premise and to the postulation of a new premise. To be more precise, the errors in the octants give rise to the following question:

(7) Which curve accounts for the eight minute errors in the octants?

The answer to (7) was, of course, the oval. Here we see an important pattern of knowledge revision. The anomalies that lead to the abandonment of the original hypothesis suggested a new, improved one. Hence, the pattern of knowledge revision involved a piece of reasoning, employing a kind of feedback loop between the original and corrected hypothesis.[21] The shortcomings of the circle hypothesis gave rise to the oval hypothesis by conditioning the form of the new hypothesis. Analogous patterns of knowledge revision can be extracted from the other parts of Kepler´s inquiry as well (see next section).

Kepler has to accommodate the oval hypothesis theoretically into his background knowledge. This turned out to be a difficult task. For one thing, mathematical properties of the oval curves were not known at the time, and Kepler had to take a perfect ellipse as a mathematical auxiliary by which he could approximate oval (mathematical properties of perfect ellipses had been known since antiquity). In terms of the I-model, the answer

[21] For an account of this kind cybernetic reasoning in discovery, see Blachowicz (1987), (1989).

(8) The oval-shaped curve accounts for eight-minute errors in the octants.

was not conclusive for Kepler since the following conclusiveness condition did not hold:

(9) Kepler knows what mathematical properties the oval curve has.

On the other hand, the properties of ellipse were known to him, so that the analogous conclusiveness condition for ellipse is true, and although (9) was false, Kepler could get (approximative) answers to his questions which presuppose the oval since ellipse approximates it. Eventually, at the final stage, he realized that the ellipse had important astronomical applications: it was more than a mathematical auxiliary.

Another difficulty was that he had to explain the oval from his physical principles. He had to explain how the mechanism of the central power emanating from the sun cum the magnetic attractions and revolts could produce the oval-shaped orbit. We can perhaps maintain that before that the oval was only a potential answer to (7). This would stress the role of physical principles as conclusiveness conditions for the geometrical hypotheses.

The solutions to these problems were also found from the earlier difficulties. Kepler noticed that if he let Mars move non-uniformly on the epicycle of the previous model, the result is the oval orbit. This was the geometrical part of the solution. However, the physical explanations given to the previous models also applied to the oval-based model, thus incorporating the physical principles into it.

4.7. Final battles

At this stage, Kepler calculated longitudes using an auxiliary ellipse and assuming the area method. Now the calculations resulted in opposite errors when compared to the previous ones in which the circle premise were used. The errors were again of about eight minute in the octants, but their signs were reversed. He then tried to construct yet another model, and adopted again the physical libration theory according to which the planet can oscillate to and fro around the Sun. Finally, he reasoned that Tycho´s data agree with his new model if the orbit of Mars is just midway between a circle and an auxiliary ellipse.[22] But the midway between a circle and an ellipse is an ellipse. In this way, he finally came to the ellipse hypothesis and achieved calculations which accorded with Tycho´s data.

The final battles of Kepler´s inquiry involved many errors and dead ends. Some of these errors occurred in the calculations, others were perhaps consequences of the stubborn reliance on the old models and thinking habits. The correct ellipse hypothesis could have been invented long before Kepler actually took it seriously. The reason for this seemed to be that he could not find either physical or geometrical justification for it. Even later the elliptical orbits presented for Kepler a kind of anomaly in the general structure of the universe. Here we see again the conclusiveness conditions at work. Ellipse was not a conclusive answer until the physical and geometrical conditions were found that rendered it plausible.

The most important step to the final approval of the ellipse occurred when Kepler was examining the breadth of the lunula between the auxiliary ellipse and the circle within which the ellipse was placed. Calculations showed that this breadth was too large. The original breadth was 858 units of the radius whereas the corrected value was 429 units of the radius (i.e. the radius=100 000). At first, he could not find any reason for this result. In our terminology, he posed a why-question:

(10) Why is the breadth of the lunula only one half of the value calculated from the model?

The answer to this question was, according to Kepler, found accidentally (AN, Chap. 56, pp. 543, see Koyré 1973, p. 253). Kepler writes:

> [Q]uite by chance I hit upon the secant of the angle 5°18´, which is the measure of the greatest optical equation. And when I saw that this was 100 429, it was as if I were awakened from sleep to see a new light, and I began to reason thus. At the middle longitudes the lunule or shortening of the distances is greatest, and has the same magnitude as the excess of the secant of the greatest optical equation 100 429 over

[22] Libration theory and oval hypothesis were equivalent to ellipse hypothesis, as Kepler finally noticed: "They stand or fall together".

> the radius 100 000. Therefore, if the radius is substituted for the secant at the middle longitude, this accomplishes what the observations suggest.

In other words, Kepler could explain the result when he could incorporate it into his physically interpreted geometric model. Moreover, this incorporation usually involved the means to revise and improve the current model. In the above case, for instance, the explanation eventually leads Kepler to consider the ellipse halfway between the auxiliary ellipse and the circle around it. We can also observe the role of chance in discovery: things like surprising numerical relations between apparently unconnected elements can enhance the discovery decisively. The most important phase, however, is still the one involving careful reasoning. This feature is also present in the above example.

4.8 Summary

I have tried to show how some crucial parts of Kepler´s inquiry can be reconstructed by the I-model. Let us now make a brief summary.

To begin with, the interrogative steps of Kepler´s discovery process were usually steps in which he compared the results of his theoretical calculations with Tycho´s data. Such single interrogative steps usually had an internal structure of their own, viz., they contained series of more specific questions concerning the observationally determined values of particular locations of the Sun, Mars and the earth in different phases of their period. Furthermore, many answers were calculated by means of the vicarious hypothesis which itself was established by Tycho´s observations. Here we see an example of the hierarchical feature of inquiry: the upper level inquiry uses the results established on the lower level.

Some stages involved only deductive steps. This was the case at the final stage when Kepler realized that the oval-orbit hypothesis together with his libration theory were equivalent to the ellipse-orbit hypothesis. Typical lines of inquiry, however, included both deductive and interrogative steps. Many deductions between the interrogative steps consisted of complex mathematical arguments. Trigonometric and geometric calculations were an essential deductive part of Kepler´s inquiry.

The discovery of elliptical orbit and the area method was, then, a kind of unintentional byresult of several interrogative inquiries. These inquiries lead to a series of modifications in the initial theoretical premises T and formed the battles of Kepler´s war on Mars. In the beginning he used the previous models of Ptolemy, Copernicus and Tycho Brahe, and arrived at his vicarious hypothesis. Subsequently, he started another inquiry and constructed another model. In this model the equant point was replaced by the area principle and the epicycle theory. However, he was not able to achieve conclusion C (i.e. the acceptable planetary model of Mars) from these modified premises T´ either, so that he finally started to doubt also the circle hypothesis. In other words, he tried to achieve C with still another modified set of premises T´´ where the circle hypothesis was replaced by the oval hypothesis. The final solution with the ellipse came when even the oval hypothesis failed. Every step in this process involved careful attempts to determine a new form of a theory. In this way, he finally achieved C or rather, a modification of C, C´. As I discussed earlier, this C´ was a new version of the planetary model of Mars which was not based on circular orbits and such devices as equant points. Instead, it was based on elliptical orbits with the sun at one focus.[23]

5. Kepler´s Strategies of Discovery

Our account of Kepler´s inquiry justifies some interesting conclusions. One is that Kepler always had good reasons to do what he did in the several battles of his war against Mars. He made strategic evaluations of different moves which directed his inquiry through difficult problem areas. Kepler himself characterized his inquiry as a war against Mars, and wars, as we know, are won by good strategies.

In particular, it seems that the strategic principles which direct modifications of background knowledge are the most essential factors in

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[23] We must distinguish between ellipse hypothesis as a premise of Kepler´s inquiry and as an ingredient of the conclusion C´. Premises are generic expressions such as "the orbit of Mars is an ellipse" whereas the conclusion, the specific planetary model has a more definite ellipse as an ingredient, expressed by the sentences such as "the orbit of Mars is the ellipse with the properties x, y, z,..".

scientific innovations. Most of Kepler's strategies are local, depending on domain-specific information. But there were also some frequently used general argument strategies or argument patterns.

One important strategy, to raise questions and, in this way, to revise existing knowledge, was already discussed in the previous section. I shall call it *model revision pattern* (MRP, for short). The essential feature of MRP is that the old model or hypothesis is corrected by the help of errors or anomalies which challenged it in the first place. Hence, Darden (1991) calls MRP-type strategies strategies for anomaly resolution.[24] It was noticed that Kepler used such reasoning in AN. There are also other variants. Stephenson (1987, p. 17) describes a method which he calls the rule of false position or *regula falsi* and shows that it is used by Kepler (e.g., pp. 42-44).[25] Writes Stephenson:

> The rule of false position, or regula falsi, is a simple way of solving difficult problems iteratively. One assumes a value for the unknown quantity, then computes other quantities dependent upon it. If the problem has a unique solution, one will eventually obtain a contradiction, unless the assumed value was in fact correct. When the contradiction occurs, one adjusts the initial value and tries again. In well-behaved problems, comparison of the results from different trials permits one to converge on a correct solution rapidly, if tediously.

Obviously, this rule can be interpreted as a token of MRP. The inquirer can correct the hypothesis or invent a new one by assuming a value for an unknown parameter and by adjusting it iteratively. Kepler used this method, for instance, when he constructed the vicarious hypothesis.

Now we must examine whether AN contains other similar strategic reasoning patterns. One influential proposal was made by Charles Peirce and Norwood Hanson. They introduced a reasoning pattern called

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[24] She also distinguishes between monster and model anomalies. The former are resolved by monster-barring strategies (following Lakatos's 1975 account) which do not change the theoretical model but show that the anomaly did not after all fall to the scope of the model. The latter are resolved by changing the theoretical model, i.e. deleting and subsequently adding some component(s) to it. It is clear that my model revision strategies fall to this latter category.

[25] A more detailed account is given by Small (1963:180-184).

abductive or retroductive inference, and claimed that it accounts adequately for Kepler´s reasoning in AN. The general schema of abductive inference can be presented in the form of the following argument (Hanson, 1958:86):

1. Some surprising phenomena P is observed.
2. P would be explicable as a matter of course, if H were true.
3. Hence there is reason to think that H is true.

Kepler´s inquiry in AN was, according to Peirce, "the greatest piece of retroductive reasoning ever performed." Hanson followed Peirce in his insistence that Kepler´s reasoning conforms to the above schema. However, the details of Hanson´s analysis were different.[26] He claimed that abductive inference can help the inquirer to see general intelligible patterns in the evidential data. What this seeing comes to is a kind of "conceptual Gestalt-switch": the puzzling and confusing phenomena appears suddenly as a systematically arranged pattern. This is achieved by inventing a hypothesis which explicates or explains the data "as a matter of course."

In Kepler´s case, the conclusion of the abductive inference was the ellipse hypothesis. By means of this inference Kepler could finally see the right pattern in Tycho´s data, and discover the correct elliptical pattern for the orbit of Mars. Hanson writes about this reasoning as follows (1958:90):

> Theories put phenomena into systems. They are built up "in reverse"-retroductively. A theory is a cluster of conclusions in search of a premiss. From the observed properties of phenomena the physicist reasons his way towards a keystone idea from which the properties are explicable as a matter of course.

Although Hanson´s abductive argument contains several deficiencies, there also are many plausible features in his discussion of Kepler´s discovery. I think that Hanson´s insistence on the reasoning from the data "in reverse" to theories or hypothesis is an interesting idea if we

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[26] See Kleiner (1983: 280-87) for a discussion of the differences between Peirce and Hanson.

remember the essential role of background theories in this process. Furthermore, this reverse process is not a holistic one-step argument. Instead, it can be arranged in the form of a complex logical argument which can lead the inquirer to a discovery of new hypothesis. Essential to this process is that the inquirer can doubt and even abandon some of her premises. According to our model, this reverse process as well as the knowledge revision part of it can be systematized by conceptualizing it as a question/answer-argument.

We have noticed in several junctures how important the rich background knowledge store (theories, models, facts etc.) is for the creative inquiry. But on the abductive account of Kepler´s discoveries these considerations seem to be forgotten. Hanson acknowledges only the role of facts, and Peirce relies on vague biological principles when he tries to argue for the important role of abduction within human inference habits.[27] Abductive reasoning can be an important strategic reasoning pattern if it is augmented by the above mentioned theoretical ideas. Something along these lines has already been done.[28] Kleiner (1983) tries to improve on Hanson´s account of Kepler. He emphasizes the role of background knowledge and contends that Kepler´s background assumptions were largely fixed before his war on Mars even began. In *Mysterium Cosmographicum* Kepler already adopted the methodological maxims which, according to Kleiner, form the background of his war. To be more precise, Kleiner claims that these maxims form a metaphysical blueprint in a sense of Maxwell (1974), and that Kepler´s reasoning in *Astronomia Nova* accords with the rules of rational assessment of metaphysical blueprints given by Maxwell. These rules offer criteria for preferring some hypotheses and research programs over others.

It is true that the metaphysical assumptions inherited from the period of *Mysterium Cosmographicum* loomed behind Kepler´s reasoning in AN.

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27 See Kleiner (1993), Chap 1, and Kapitan (1992), for the discussion of Peirce´s view of abductive inference. In his later writings, Hanson gave much more weight to the role of background knowledge in abductive inferences. See Hanson (1965), for his final views of this subject.

28 There have been attempts to interpret abductive reasoning as inference to the best explanation. See, for instance, Achinstein (1970), (1971), Lipton (1991). In this interpretation the background information enters the picture along the notion of scientific explanation. See Sintonen (1984), (1989), for such notion of explanation.

For instance, the strong belief that archetypal forms such as regular solids are manifested in the structure of the universe was surely a part of his background beliefs. On the other hand, the role of these metaphysical views should not be exaggerated. The influence of harmonic considerations to Kepler´s thinking were much more visible in *Mysterium* and *Harmonice Mundi* than in the strictly astronomical works such as AN. In this latter work the *aposteriori* nature of astronomy is (at least implicitly) emphasized. It was Tycho Brahe´s influence and his careful observations of celestial bodies which drove Kepler away from the one-sided metaphysical theorizing.[29]

Furthermore, Maxwell´s rules, also used by Kleiner, do not seem to offer a sufficient account of Kepler´s methodological maxims. Take as an example Rule 1 (Kleiner, 1983:292; Maxwell, 1974:258):

Rule 1: Other things being equal, choose that aim, that blueprint which is the most intelligible, simple, [general], coherent, harmonious, explanatory, unified, beautiful. (In part at least this will mean choose that blueprint which promises to lead to the development of the most intelligible, simple, etc. testable scientific theory.)

Simplicity, coherence and other methodological virtues are without doubt important strategic considerations but can this rule bring any light to Kepler´s reasoning? I think that their manifestations in Kepler´s case are not captured by these rules. They are simply too general to be of much assistance. The long list of scientific desiderata in the above quote does not help us to clarify these very notions either. What, for instance, is meant by simplicity? And was Kepler´s notion of simplicity the same as ours? It is true that these kinds of goals do play a role in scientific inquiry, even in Kepler´s inquiry, but they are not independent of historical context. Hence, these rules are not sufficient for our purposes.

According to Kleiner, Kepler´s reasoning included three types of abductive inference. Besides the standard form he discusses the notions of converse and comparative abductive inference. They are presented by the following schemata:

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[29] Mittelstrass (1972) discusses this shift in Kepler´s thinking.

1. If P were true, then P would be explained as a matter of course by preferred hypothesis H.
2. Hence, there is reason to believe P true.

1. Phenomenon P is observed and is surprising.
2. Hypothesis H provides a better explanation of P than alternative H´, ...
3. Hence, there is reason to prefer H to H´, ...

The use of the three types of abductive inferences improves Hanson´s account, but it does not save it. The crucial fact conveyed by Kleiner´s schemata is that Kepler´s reasoning involved many types of inferences. However, there is no reason to assume that these conform only to the abductive forms or that there are only three of them.[30] Abductive schemata also miss the essential role of local strategies.

Local strategies depend on factual knowledge of the context of inquiry. It is evident that Kepler employed them throughout his inquiry. Some of them were inherited from Ptolemy, Copernicus and other astronomers, some were invented by Kepler himself. One interesting example concerns the three methods he used when trying to establish the angle between the orbit of Mars and the ecliptic (i.e. the inclination of the orbit). I shall rely on Small´s account (1963:167-174). He writes:

> After determining, at least nearly the longitude of nodes, the remaining and most important business was, to investigate the inclination of the orbit to the ecliptic. For this purpose Kepler employed three methods. One, which is applicable to all the planets except Mercury, requires observations of latitude made in the limits, when the distance of the planet from the earth and the sun are equal; and it supposes that the mutual ratio of the orbits and the heliocentric distance of the planet may be nearly, at least, determined by some of the former theories.... [geometrical description]...In the same investigation Kepler employed another method, equally of his own invention, and which required, neither any pre-conceived opinion concerning the ratio of the orbits, nor the aid of calculation to distinguish the observations proper for the

[30] Snyder (1997) distinguishes and gives examples of four types of inferences, enumerative, eliminative, causal and analogical, used by Kepler in AN.

> purpose....[geometrical description]....To confirm this conclusion from so many observations, Kepler also employed the method originally used by Copernicus, though it supposes a pre-conceived opinion concerning the ratio of the orbits...[geometrical description].

This quote nicely illustrates the features of local strategies. First, it is important to notice the assumptions required for the proper application of a method. These assumptions constrain the range of application in which the local strategy helps the inquirer to reach her goals. Second, it shows that these strategies are tools of both discovery and justification. Kepler used the first two methods (of his own invention) to discover the right angle, and the third one (the method used previously by Copernicus) to confirm the result. This supports my previous argument against the separation of discovery and justification. Third, it indicates that good strategies also have to be invented. The creative part of inquiry is not restricted to the discovery of results alone: it ranges from the invention of methods to the justification of the results.

6. Conclusion

The conclusions of my discussion should now be clear: the I-model offers a fairly realistic reconstruction of Kepler's inquiry by stressing the rational, strategic aspects of scientific reasoning. What it cannot offer a ready-made rule book of scientific discovery which could determine the inquirer's choices in every possible epistemic situation.

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