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Discovery on purpose?
Toward the unification of *Paradigm Theory* and the *Theory of Inventive Problem Solving* (TRIZ)

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Abstract: This essay relates Thomas Kuhn's Paradigm Theory with Genrich Altshuller's Theory of Inventive Problem Solving (TRIZ for short). Despite their clearly divergent cultural roots, both understand paradigm shifts as the result of problem-solving processes — Kuhn in science and Altshuller in technology. In contrast to Kuhn, Altshuller used paradigm shifts to study creative problem solving in technology in order to make invention on purpose possible. He summarized his finding in the *Algorithm of Inventive Problems Solving* (ARIZ), which, as we will show, can be made explicit in a more general system theoretical framework. This allows for its application outside of the technological domain without relying on crutches such as metaphorical analogies. In order to demonstrate the application of this generalized version of ARIZ, we reconstruct one of the most famous paradigm shifts in the history of science — the shift from the Ptolemaic geo-centric system to Copernicus' helio-centric one.

Keywords: ARIZ, Paradigm Shift, Science.

1 Introduction

From an epistemological point of view, Genrich Altshuller's *Theory of Inventive Problem Solving* — TRIZ — [1] is built upon four crucial decisions:

- (i) Technological objects are viewed from a system perspective.
- (ii) The focus of attention is on the development of these objects as systems.
- (iii) The development is studied in terms of concrete changes within the inner-systemic hierarchy.
- (iv) These changes are reconstructed as if they were the results of intentional problem solving.

Altshuller assumed that studying the development of technological systems in this way could serve as a suitable window into the black box of *creative problem solving*. What is more, he showed that a clear understanding of the logic that underlies these processes can make creative problem solving teachable. The further TRIZ developed, the more the character of Altshuller's epistemological decisions crystalized. This can be best appreciated by following the roughly 30-year development of the *Algorithm for Inventive Problem Solving* — starting in 1956 and ending in 1985 — with Altshuller's final version: ARIZ-85C [2]. In contrast to the earlier versions [3], the latest has almost entirely stripped off any reminiscence of its original domain: technology. Only a few terms, such as "tool," are reminiscent of the engineering discourse. Upon closer examination, however, they turn out to be placeholders for more abstract vocabulary concerning systems in general. We will call it *vocabulary for systemic thinking*.

The goal of our paper is to bridge the gap between the application of ARIZ in technology and other domains — particularly science. To do so, we will develop the *vocabulary of systemic thinking* as far as it is needed to express the structure of ARIZ in more general terms.[1] Then, we will address development in science much as Altshuller addressed development in technology. For this purpose, we introduce Thomas Kuhn's famous three phase distinction of *pre-normal*, *normal* and *revolutionary science* [4] and draw the attention to Altshuller's distinction of two different types of scientific discoveries — *new explanations* and *new detections* [5]. After matching Kuhn's distinction with Altshuller's, we will limit our attention to the application of ARIZ to explanatory discoveries alone. Having outlined to which extent explanations can be understood as *explanatory systems*, we will finally apply ARIZ, in its system theoretical form, to one of the most famous paradigm shifts in the history of science: the transition from the Ptolemaic to the Copernican planetary system. We conclude with suggesting the unification of both paradigm theory and TRIZ within a system theoretical framework. Since the goal of our paper is to show why and how ARIZ can be used in science, we will say very little about its application to technology. For a deeper understanding, we recommend the study of Altshuller's own example [2, 6].

2 Elements of a Vocabulary for Systemic Thinking

Systems can be described as finite sets of elements that are organized according to certain rules. These elements stand in relation to one another such that the system is more than the mere sum of its parts. The set that comprises the set of all elements of a system and the set of all the relations between them is called the *system structure*. While this structure determines the system's (context-dependent) behavior — i.e., the set of all of its states over time —, the same behavior might be realizable by alternative system structures [7].

That the concept of systems is primarily a pragmatic methodological category that helps to describe, explain and control subjects of our interest can be seen from the way the term *element* is used. Whether or not it is convenient to consider an element of a system to be (i) *elementary* and not in the need for further decomposition or (ii) itself a system with its own *system structure* depends upon the pragmatic context of the analysis. An element of a system S that has its own *system structure* is called a *sub-system* of S. In return, a system S that has another system S' as one of its elements, is called a *super-system* of S'.

From a subjective standpoint, a system's behaviour — or parts of it — can appear to be desirable or undesirable in certain contexts. Although most artificial — i.e. human-made — systems are designed for a purpose that is desired by someone, parts of their behaviour can be undesirable. A purpose can be described as a hierarchically ordered system of aims [7], where primary aims can be distinguished from secondary ones. Primary aims are expressed in the form of answers to the question of what the system was designed (or put into place) for, while secondary aims play an auxiliary role. The latter are either means to the end of achieving other aims, or they express a certain desirable behaviour of the system — for example, the elimination of some undesirable side-effect.

Thanks to their *system structure*, systems have the capacity to achieve primary and secondary aims. A system's capacity to achieve a primary aim will be called a *primary function* of the system and its capacity to achieve a secondary aim a *secondary function*. Note that, according to this definition, the term function is only used for capacities that are considered desirable (which does not exclude the possibility that the enabling structure might be the cause for effects that are considered undesirable). As a consequence, a change in the structure of a system that results in the loss of a function without further compensation yields undesirable effects (since a desirable effect can be understood as the negation of an undesirable effect).

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[1] At first sight, it might seem that a similar effect could be achieved by comparing the TRIZ-specific ontology with the specific ontology of the target domain. This, however, would only forge the foundation for an application of TRIZ in this specific target domain. In contrast to this strategy, we claim that TRIZ is itself an application of a more general framework of system thinking in the field of technology. Its ontology can be seen as an effect of this application. By spelling out this general way of thought, we hope to provide a framework for its application beyond the technical sphere.

The phenomenon of pragmatic relativity that shows in the use of the term *element* also applies to the distinction between the terms *primary function* and *secondary function*. On the one hand, the primary function of a system might only be a secondary function when viewed from the perspective of its super-system. On the other hand, a sub-system might only be in charge of a secondary function within a wider system. However, when only looking at the very same sub-system, the former secondary function might turn out to be the primary function.[2]

Sub-systems (or elements) that provide a primary function will be called *primary sub-systems* and those providing secondary functions will be called *secondary sub-systems*.

3 Thomas Kuhn's Distinction of Pre-normal, Normal and Revolutionary Science

Having developed the vocabulary needed to view Altshuller's approach from a *systemic perspective* we can now turn our attention towards the concept of *development* by building upon Thomas Kuhn's *Structure of Scientific Revolutions* [4]. Summarising the findings from his studies in the history of science, Kuhn describes a pattern of evolution in science by distinguishing three phases: (i) Pre-Normal Science, (ii) Normal Science, and (iii) Revolutionary Science. Drawing on the tradition of American pragmatism, Kuhn explains these three different phases in terms of different types of problem solving. During the first phase, it is not yet clear how to best frame the problem. Consequently, different schools develop their own explanatory strategies, which compete with one another until an explanatory paradigm is developed that outcompetes alternative approaches such that researchers now rely on this paradigm when coping with the problems in their field. Kuhn calls this phase *normal science.* For example, when the Ptolemaic model was established, the European history of astronomy entered such a phase of normal science. By sticking to this paradigm, astronomers were able to solve well-defined problems, such as predicting the position of certain *vagabonds* at a given time (*vagabonds* was the term for moving celestial bodies at this time). Accordingly, one major parameter for the model's improvement was the accuracy of predictions. Among other things, the vagabonds moving on spheres around the Earth were themselves placed on further spheres in order to account for the appearance of planets moving backward. The more the model's accuracy was improved, the more obvious an internal contradiction in the model became: minor improvements in accuracy caused major deterioration in simplicity, even though full accuracy could not be achieved. When the Ptolemaic geo-centric paradigm was replaced by Copernicus' heliocentric one, the model's simplicity improved dramatically. Kuhn calls such replacements *paradigm shifts*. They are the result of problem-solving processes

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[2] This relativity of the terms primary and secondary function points to a deeper problem in approaches of systemic functional analysis in non-artificial systems such as [8] and [9]. Analyzing an object as a system is, in the first place, a methodological choice made by an inquiring subject for the sake of explaining some phenomenon. What the roles of a system's parts are (and the way in which these parts are individualized, too) partly depends on the explanatory choice of the inquiring subject. Take for example a human's heart: If we choose to consider its role in the context of blood circulation, we will conclude its role is to pump blood. If, however, we want to explain the entire sound spectrum in human bodies, the role of the heart will consist in creating a more or less rhythmical beat. This criticism of arbitrariness in systemic approaches has been prominently articulated by proponents of etiological theories [10, 11]. Moreover, etiologists argue that because of its dependency on subjective explanatory choices, systemic functional analysis cannot account for the normative dimension of proper functioning. In other words, whether or not a system's part works well cannot be judged on the basis of systemic approaches alone. All they explain is how the system actually behaves. Whether or not a heart, for example, beats too quickly or too slowly, too much or too little, exceeds the limits of the explanatory framework. As a consequence, the value judgement becomes again a matter of subjective consideration. Etiologists try to solve both of these problems by including the dimension of history into their understanding of functionality. Looking for the proper function of some part P in a system S, they argue, means to ask the question: *How come that P is a part of S?* Take for example a breathing apparatus that contains a filter. One could ask: *How come this filter is part of the breathing apparatus?* Moreover, they argue it can be said that the proper function of P in S is the effect E if and only if *P was selected to be a part of X, because of having the effect E in X.* In the breathing apparatus, the proper function of the filter is to filter the air just because the designer of the breathing apparatus put it in for the sake of achieving exactly this effect. In engineering this selection implies conscious decision-making, while it is a matter of natural selection when it comes to biological systems [11]. In other words, the proper function of the heart — to pump blood —, etiologists would argue, is the effect for the sake of which it has been picked by natural selection. Note that this framework also allows to assign multiple proper functions to a system's part in case that this part was selected for multiple effects (for a more detailed discussion of this debate see [12]).

during the phase of *revolutionary science* and foster a redefinition of a discipline's paradigm, yielding a new phase of *normal science*.

4 Discoveries as *Detections* or *Explanations*

During all three phases, scientists aim at producing knowledge — some of it being called *discovery*. As Altshuller points out in a paper on creative problem solving in science [5], the term "discovery" refers to two different phenomena: *new detections* and *new explanations*. Explanation as purposeful practice is crucial for science and faces different kinds of challenges during each of Kuhn's three phases. During the phase of pre-normal science, there is no established paradigm that the explanation could draw upon. For this reason, scientists need to come up with their own groundbreaking approaches. This leads to competition between various attempts. In the phase of normal science, when paradigms have been established for the vast majority of scientists, explanation consists in the application of such established paradigms. During the phase of revolutionary science, however, a standard paradigm is challenged by a new and presumably superior way of explanation that can, for example, account for anomalies that were not explicable by means of the former.

Unlike the development of most explanations, detection of something new can be the result of both purposeful action and lucky coincidence. Here again, the nature of each of these two types of detection differs during the three phases of pre-normal, normal, and revolutionary science. Matching Altshuller's three types of discovery with Kuhn's three phases allows us to set up a 3 by 3 matrix (see Table 1). It illustrates nine different types of discoveries with examples from the history of science. While all of these matter for development in science, we will limit our focus in this paper to the last row, which covers explanation.

In the next chapter, we will give an example of how explanations can be viewed as *explanatory systems* and thereafter apply ARIZ to reconstruct in hindsight the respective paradigm shift from a problem-solving perspective. Discoveries that are new detections can be viewed similarly by studying them as *experimental systems*. This, however, goes beyond the scope of our paper.

Table 1: Altshuller's three types of discoveries — accidental detections, purposeful detections, and purposeful explanations — are viewed in Kuhn's pre-normal, normal, and revolutionary phase.

Types of Disco-very	Pre-normal Phase (no established paradigm)	Normal Phase (established paradigm)	Revolutionary Phase (established paradigm is challenged)
Detec-tions by accident	A phenomenon is accidentally detected during research in a field for which no dominant paradigm has yet been established.	While doing research in the tradition of an established paradigm, anomalies are detected that cannot be explained.	The established paradigm is already challenged, while an unexpected phenomenon is unintentionally detected.
	Example: While conducting experiments with a dissected frog nearby an electrical machine, Luigi Galvani's assistant accidentally touched an inner nerve with a scalpel so that the frog's limbs twitched. A debate with at least three competing schools arose [13].	Example: Experimenting with air, Lord Rayleigh and Sir William Ramsay found out that the nitrogen extracted from the air was by 0.5 % heavier than the chemically produced element. Looking for the cause, they discovered Argon [14].	Example: Heike Kamerlingh Onnes synthesized liquid Helium, then studied current flows at low temperatures, discovered super-conductivity and detected what has later been studied under the name super-fluidity [15].

Detections on purpose	There is no paradigm that can explain a phenomenon that was detected as the result of purposeful experimentation.	Investigation of a phenomenon, for which the established paradigm suggests a certain outcome.	The established paradigm is already challenged and based on a new paradigm a heretofore undetected phenomenon is detected on purpose
	Example: Michael Faraday experimented with electric currents and magnets in order to determine the laws of induction of currents, which resulted in the detection of phenomena of electro-magnetism [13].	Example: Based on his general theory of relativity, Albert Einstein predicted gravitational waves in 1916 (Einstein, 1916). When his theory became accepted, scientists started to look for these waves. In 2015, they were finally detected [16].	Example: In 1915, Albert Einstein predicted the bending of light by the gravity of the sun. Sir Arthur Eddington and his team took advantage of a total solar eclipse in 1919, detected the deviation and contributed to the acceptance of Einstein's General Theory of Relativity [17].
Explanations on purpose	In the absence of an existing paradigmatic way of explaining certain phenomena, attempts of explanation are undertaken.	Phenomena are explained with the help of an established paradigm.	The established paradigm is challenged by a new paradigm that claims to be superior.
	Example: In the early days of studying phenomena of electricity, a group of theories existed that considered attraction and factional generation as fundamental electrical phenomena [4]	Example: The paradigm of covalent bonds allows for explanation of a compound's chemical properties even if this substance has not yet been synthesized.	Example: Nikolas Copernicus challenged the well established geo-centric model of planetary motion by suggesting his helio-centric model [4].

When it comes to studying creative problem solving in science, the focus of attention is to be put on the creation of new kinds of explanations that either yield a shift from the pre-normal phase to the normal phase or successfully end a revolutionary phase.

5 Scientific Explanation as System

Equipped with the above definition of *system* and the brief excursion into the history of science, the difference between technological objects and scientific explanations can be outlined on a common ground. Technical objects can be viewed as *artificial systems* (a) insofar as they are designed for certain purposes, and (b) insofar as they can be decomposed into functional parts. (c) If one of these parts was missing, actual or potential undesirable effects would arise within the system or its context (at least if the part's function was not somehow compensated or made irrelevant). Scientific explanations or theories, in return, can also be viewed as *artificial systems* [12, 13] — at least (a) insofar as they are designed for explaining something in certain contexts (explanatory purpose), and (b) insofar as they can be decomposed into functional parts. (c) As mentioned before, parts are *functional* if taking one of them out results in effects that are undesirable in some context. In the case of scientific explanation, these effects most often turn out to be epistemic in nature. Potential *sub-system—system—super-system* relations can be found in both the technological and the epistemic context.

5.1 Explanatory Sub-systems

We can analyze the system structure of technical objects by singling out their components and functional relations. These components might themselves be systems and appear from the perspective of the analyzing subject as *sub-systems*. Something similar happens in explanations, which are based on the use of concepts in judgements and inferences. Most of the time, we need additional concepts, judgements and inferences in order to explain the ones that we are using in our explanations. Moreover, digging deeper into the *system structure* of explanations (the concepts, judgements, and inferences) leads us to the epistemic practices and the experimental technologies that provide referential data.

Take for example the Ptolemaic geo-centric model that was used for predicting the position of vagabonds at a given time. An astronomer from the Ptolemaic tradition would approach this task with the help of her explanatory model. When asked for the exact reasons why this and not another position was predicted, she would have to refer to the system structure of her explanatory model. Her simplified answer might look like this: The vagabond revolves with speed S_1 around a point P_1, while P_1 revolves with speed S_2 around a point P_2 that is close to the Earth (see Figure 3).

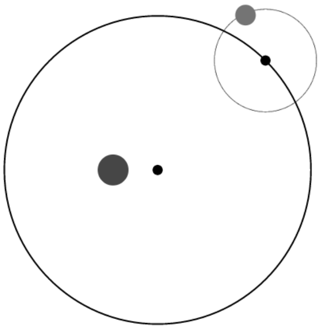

Fig. 3. Simplified version of an elementary explanatory unit in the Ptolemaic model: A planet revolves in epi-cycles (smaller circle) around the Earth, which is close to the centre of the planet's revolution.

This formulation alone already refers to at least eight explanatory concepts: 1) speed S_1, 2) point P_1, 3) speed S_2, 4) point P_2, 5) revolution around P_1, 6) revolution around P_2, 7) the vagabond in question and 8) the Earth. Given each of these concepts, we could ask for further explanation, for example: *What is speed?* — and at the time of Ptolemy we might have received an answer like: The speed of a moving object tells us how far the object gets in a certain amount of time (see for example [14]). In other words, the explanatory concept *speed* appears to be an *explanatory sub-system* in Ptolemy's *explanatory system* of the vagabonds' motion. The same holds for the other explanatory concepts listed above.

5.2 Explanatory Super-systems

From the above definition of system, we also derived the concept of a super-system. Technological systems, for example, can merge and build such super-systems: Multiple computers connected as a network build, for instance, the internet. Likewise, we can join explanatory concepts in order to explain a phenomenon that is more complex: Among others, the concept of movement, for example, could be applied to (i) a body and a straight line or (ii) a body and a circular line. The first might result in the concept of a body moving straight forward and the latter in the concept of a body revolving around something.

5.3 Hierarchy and Complexity

It follows from the definition of *system* that each system might be built from multiple sub-systems and that likewise, each super-system consists of more than one system. This means that complexity increases no matter where we start to explain a phenomenon. Let us distinguish two perspectives on hierarchies of explanatory concepts — (i) *top down* and (ii) *bottom up.* (i) When explaining from a top-down perspective, we start with the help of an explanatory concept from the top of the hierarchical order and (ii) when explaining from a bottom-up perspective, we start with one from the bottom.

Potential Problems of Top-Down Approaches

Starting with explanatory concepts from the top of the hierarchy allows us to see the whole picture and to unite explanatory concepts from different domains. However, misconceptions on higher levels can block or misguide conceptual developments on the lower levels. The transition from a physically and not-only-mathematically-understood geo-centric model of planetary motion to a helio-centric, for example, was complicated by the Christian doctrine of the Earth as the center of the universe. This belief was imbedded in an overall vision of life and our (humans') role in a world created by God. Conceiving of the Earth as one planet among others was not only radical in the domain of astronomy, but also implied conceptual modifications higher up the hierarchy.

Potential Problems of Bottom-Up Approaches

Starting with a concept from the bottom in order to explain a phenomenon is a feature of reductionist strategies: A concept seems to have so much explanatory power that its scope is to be extended either to other phenomena or to other aspects. Ptolemy, for example, used a circle to model the revolution of vagabonds around the Earth. Seen from a geo-centric perspective, year by year the sun takes about 365 days for one whole cycle, Venus about 225 days, and Mars about 687 days. These regularities can be perfectly explained in terms of revolution and geometrically modeled with the help of a circle.

However, from the perspective of our Earth, it seems that both Venus and Mars move backward from time to time. The Ptolemaic model accounted for these phenomena by using the same explanatory concept again. Instead of the vagabonds themselves, the center of much smaller circles — so-called epi-cycles — revolved around the Earth. The vagabonds, in return, were revolving around the center of their epi-cycles.

Thanks to this analogous usage of the explanatory concept of *revolution around something*, the model could explain, not only the occasional backward movement, but also its periodicity and the changes in speed that the vagabonds seem to undergo during these periods. In order to improve the model's accuracy even further, additional epi-cycles where added and the Earth was slightly moved out of the center of the epi-cycles' revolutions. Although the system's predictive power increased, it became increasingly complicated (see Figure 5).

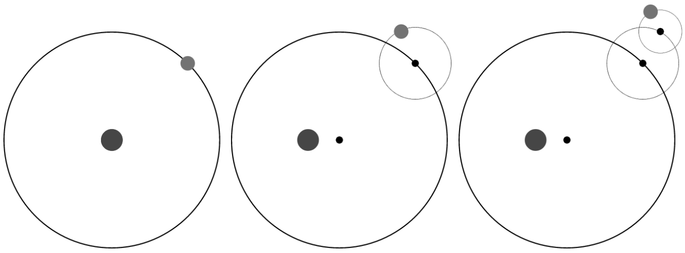

Fig. 5. The model for explaining the periodic movement of vagabonds was further extended to explain the backward movement as well.

Primary and Secondary Explanatory Concepts

Note that there is not only a historical but also a functional priority behind the use of circles in the Ptolemaic model. From a functional perspective, the role of the larger circle was to explain the periodic revolution of vagabonds around the Earth, while epi-cycles were introduced in order to explain details of this overall motion. Let us call the larger circle a *primary explanatory concept* of the model and the epi-cycle a *secondary explanatory concept*. The first has historical and, more importantly, functional priority, since the whole model would break down if the concept of the *revolution of planets around the Earth* was eliminated. It is of *primary* importance, since it directly affects the realization of the model's primary function. The concept of epi-cycles, in contrast, could be eliminated without causing the model's collapse. It is true that without epi-cycles, the model could no longer account for the vagabonds' backward movement, but it would still get the periodicity of their overall revolutions right. In this sense, the explanatory role of the epi-cycles is only of *secondary* importance.

6 Applying ARIZ-85C to the Shift from Ptolemy's to Copernicus' Explanatory System

We now possess all the distinctions needed for applying ARIZ-85C to explanatory systems in science (following the ARIZ version in [2]). For the sake of brevity, we slightly simplified the algorithm without compromising on the overall logical structure (see Figure 6). The way we are counting the steps does not fully match the original version of ARIZ-85C. We abbreviate the series of steps, since we neither go through the full analysis of the Ptolemaic system nor discuss all intra-systemic problems. Moreover, if not explicitly highlighted, we refer to ARIZ-85C simply by *ARIZ*.

6.1 Step 1 — Towards an Understanding of the System Conflict

Step 1.1: According to ARIZ, the guiding thread for the development of a system is its primary function (or its primary functions). In case of Ptolemy's system, the primary function consists in explaining the vagabonds' movement.

Step 1.2: Since ARIZ views its subject as a system with a primary function, it can be further decomposed into interacting parts or (if they are further decomposable) sub-systems. Altogether, these sub-systems have to achieve the system's primary aim — which is the original reason why it exists at all. Moreover, sub-systems often have to achieve secondary aims. A functional analysis of the Ptolemaic explanatory system reveals that the backward motion of some of the vagabonds could not be explained without the help of epi-cycles. The explanation of this backward movement, for example, is such a secondary aim.

Step 1.3: Both primary and secondary problems turn into systemic conflicts when the solution to them yields a tradeoff. As we have seen, dealing with epi-cycles yields the tradeoff between the system's accuracy and its simplicity.

6.2 Step 2 — Stating the Task to be Solved

Step 2.1: After having identified the system-conflict, ARIZ asks whether or not the conflict is due to a secondary sub-system. If so, its elimination is suggested. Since the epi-cycles are responsible for the tradeoff between *simplicity* and *accuracy*, and since they are secondary sub-systems, their elimination is suggested. Seen from a historical perspective, this decision implies that the ongoing search for solutions starts from a problem situation prior to the introduction of the malfunctioning sub-system. If, in contrast, the analysis in step 1 had concluded that the problem to be solved was due to a primary sub-system, ARIZ would not suggest its elimination because, given such an elimination, the primary aim could no longer be achieved, which would amount to an elimination of the entire system. Rather, ARIZ suggests here an extreme intensification of the requirements and conditions for the system's performance.

Step 2.2: The elimination of the malfunctioning secondary sub-system leads to a new system conflict: The malfunctioning of the eliminated sub-system disappears, but the secondary problem that had been solved before reemerges. When eliminating the epi-cycles from the Ptolemaic system the conflict arises: *The system is simple but it cannot explain the backward movement of the vagabonds*.

Step 2.3: As soon as the system conflict is clearly understood, the task to be solved can be stated in an abstract but precise way (see Figure 6): *Find a resource (within the system itself or in its environment) that — when slightly modified — helps to explain the backward movement of the vagabonds without complicating the system.*

6.3 Step 3 — Looking for Potential Resources that Might Help to Solve the Task

Step 3: In order to facilitate the creation of a solution concept, ARIZ recommends to list potential problem-solving resources within the system and its environment. In the case of Ptolemy's system, the system's center, the Earth, the Sun and the Moon (these two vagabonds never move backward) appear to be particularly interesting.

6.4 Step 4 — Creation of Solution Concepts

Step 4.1: Each resource that can be selected form the list might contribute to the potential solution. Selecting the Earth, for example, yields the question: How can the Earth help to explain the vagabonds' temporary backward motion without complicating things? The answer to this question is far from obvious.

Step 4.2: However, when asking which contradicting properties P and not-P the Earth might need to have in order to help explain the backward movement of the vagabonds, we put ourselves on the right track. We know, for example, that the Earth must be in the center of the vagabonds' movement, because that is how we observe the phenomena we want to explain. *Being in the center* is thus a property of the Earth within our explanatory system. But could it be the case that the Earth must *not be in the center* such that the backward movement of the vagabonds can be explained? Following this line of reasoning, we force ourselves to imagine the Earth as *being in the center of the vagabonds movement* (in order to explain the observations) and *not being in the center of their movement* (in order to explain their backward movement).

Step 4.3: When facing this type of contradiction — something needs to have both property P and not-P — ARIZ recommends the application of three separation principles. The goal of their application is to resolve the contradiction by finding a way in which the selected resource can have both properties in two different regards:

- 1) *Separation in time*: At time T_1, the Earth is in the center of the vagabonds' movement and at time T_2, the Earth is not in their center.
- 2) *Separation in space*: Within the spacial part P_1, the Earth is in the center of the vagabonds' movement, but within the spacial part P_2, the Earth is not in their center.
- 3) *Separation between the system and its sub-systems*: From the sub-system perspective, the Earth is in the center of the vagabonds' movement; from the system perspective, the Earth is not in their center.

While the first two separation principles do not articulate concepts that could explain the backward movement, the third gives a surprisingly clear description of what the Copernican shift is about: The Earth is only in the center of the appearances of the vagabonds' movement. We observe the overall system from the perspective of Earth (as sub-system) — in this sense the Earth is in the system's center. However, as a sub-system among others (the system perspective), the Earth itself is not in the center of the system. As soon as a sub-system (a vagabond) overtakes another, it looks from the respective vagabond's perspective as if the other would turn into the opposite direction. Only when viewed from the real center of the system, no vagabond appears to change direction.

This raises the question as to which sub-system is to be placed in the center. Here the Sun and the Moon come into play. Neither shows any backward motion, which makes them promising candidates. Putting the Moon into the center would imply that the Sun moved back and forth from time to time. Moreover, it would be impossible to make sense of the observations of any of the vagabonds' movements. In contrast, placing the Sun in the center of the vagabonds' revolutions matches the observations quite well. However, it raises the question why the Moon never changes its direction. Copernicus' answer was straight forward: While all vagabonds — the Earth included — were revolving around the Sun, the Moon was revolving around the Earth.

6.5 Step 5 — What if no Solution was Found?

In case that no solution could be found, ARIZ recommends to check whether the solution criterion in step 2 was correctly stated. If so, the restoration of the previously eliminated sub-system in step 2 is recommended; ARIZ then continues at step 2 — without the elimination of any sub-system (see Figure 6, step 2 and step 5). On this track, ARIZ recommends intensifying the conditions and requirements for the system's performance. This was Johannes Kepler's path. He had been working for Tycho Brahe, Europe's leading astronomer at the time. Brahe had been working on the improvement of tools for observing the sky and had perfected the geo-centric Ptolemaic system to an extent that outclassed the Copernican predictions. In contrast to Brahe, Kepler preferred the Copernican model for its simplicity. It's predictions, however, were not sufficiently accurate. Seen from the perspective of ARIZ, the inaccuracies were due to one of Copernicus' primary explanatory sub-systems: circular revolutions. Kepler was thus dealing with the intensified task (see step 2.1) of having to develop a fully accurate model by sticking to the Copernican paradigm. In order to do so, he had to rethink Copernicus' primary sub-system of circular revolutions. As a result, he turned them into ellipses.

7 Conclusion

We have shown that ARIZ-85C — originally designed for solving problems in technology — can be expressed in a more general vocabulary of systemic thinking. This allows for its application outside of the technological domain without relying on crutches such as metaphorical analogies. The application of this generalized version of ARIZ was tested on one of the most famous paradigm shifts in the history of science — the shift from the Ptolemaic geo-centric system to Copernicus' helio-centric one. Many more such tests are needed to evaluate whether or not the study of Kuhnian paradigm shifts can shed light upon the nature of creative problem solving in science. It seems, however, to be a promising path. Before Genrich Altshuller and Raphael Shapiro started to systematically examine the nature of paradigm shifting solutions in technology, not much knowledge about this type of problem solving was available. Kuhn's position [15] is a quintessential example of a widely shared pessimism on this topic:

> What the nature of that final stage is — how an individual invents (or finds he has invented) a new way of giving order to data now all assembled — must here remain inscrutable and may be permanently so.

Considering the abundance of examples of such shifts in the history of science and technology, this pessimism is surprising. It seems that Altshuller and Shapiro were the first who systematically studied these transformations in technology in order to gain insight into the logical operations necessary for bringing about paradigm shifts. In this way, they became the founders of the *Theory of Inventive Problem Solving* (TRIZ), which aims at making invention on purpose possible. With this paper, we want to suggest that something similar is possible in science. The goal of the resulting theory could be called *discovery on purpose*.

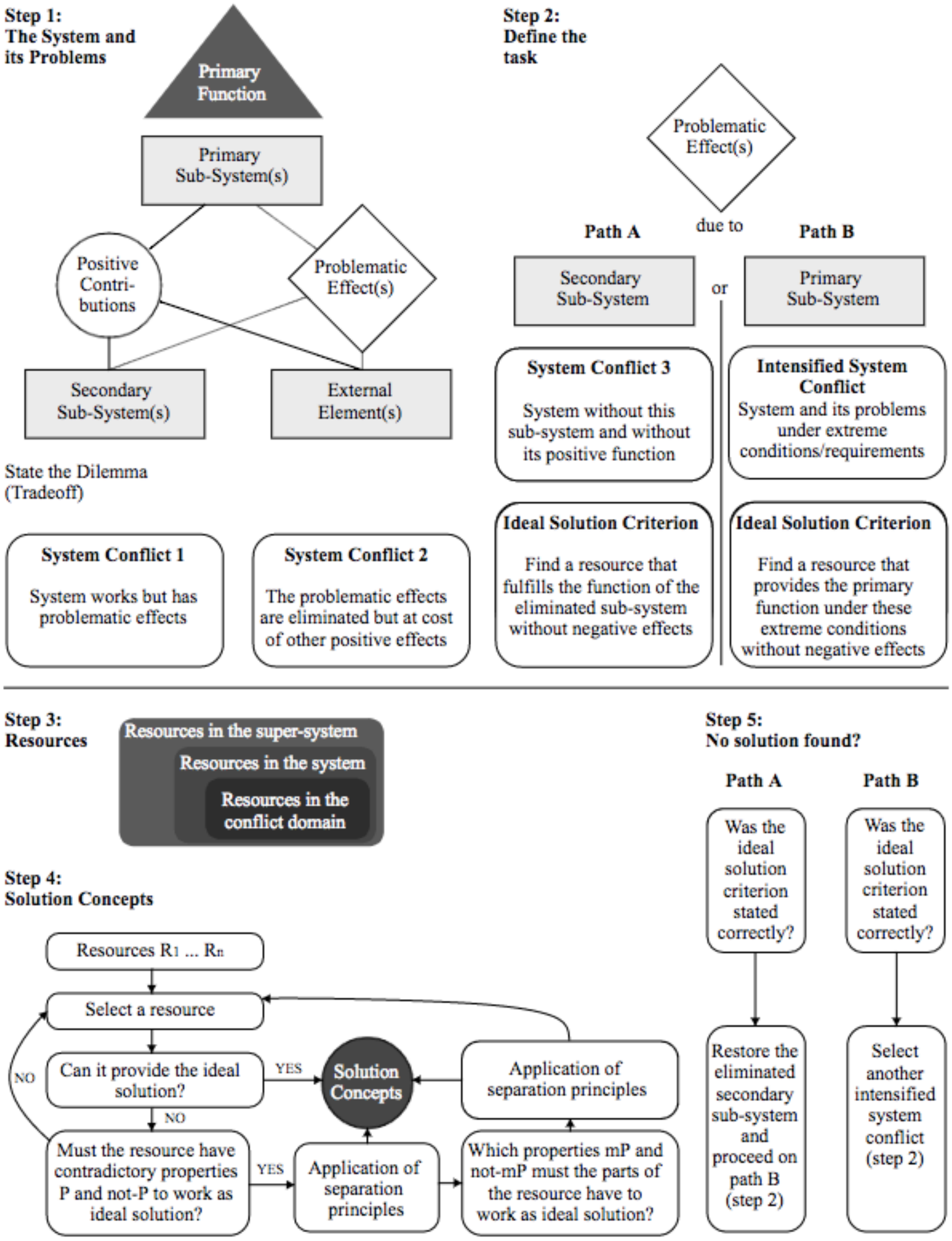

Fig. 6: General structure of ARIZ-85C

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