An Evolutionary Theory for Science and Technology

Yasuo NAKAYAMA

Abstract

In this paper, we propose a theory of scientific theory changes. We call this theory *Evolutionary Theory for Science and Technology* (ETST). ETST is an approach that is based on *Logic of Belief Structures* (LBS) and it can be used to describe historical developments of scientific activities. ETST considers a triple ⟨*theory structure*, *research team*, *research school*⟩ as the unit of scientific evolution. Research teams try to solve problems based on accepted theory structures. They also evaluate theory structures in their discipline by three epistemic values, namely *accuracy*, *expressibility* and *coherence*. These evaluation activities produce a selection process of theory structures. In this paper, we characterize ETST and demonstrate how to apply ETST to the clarification of some notions in philosophy of science and to the description of scientific developments.

Keywords: evolutionary theory, science and technology, theory structure, research team, research school, Thomas Kuhn

1 Evolutionary approaches

In the first part of this section, we describe some aspects of biological evolution. In the second part, we give a short overview of evolutionary approaches in the philosophy of science.

1.1 Concept of evolution

The *evolution* is originally a biological notion. Darwinism characterizes the evolution through natural selection. Brandon (2014, Section 2) explains the bare bones of Darwin's theory of evolution by natural

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selection as follows:

> "Typically (but not necessarily) there is *variation* among organisms within a reproducing population. Oftentimes (but not always) this variation is (to some degree) *heritable*. When this variation is *causally* connected to differential ability to survive and reproduce, *differential reproduction* will *probably* ensue."

In the philosophy of biology, there have been intensive discussions about units and levels of biological evolution. Genotypes, individuals, groups, and species have been proposed as candidates of such a unit.[*1] In this paper, we take a modest approach and propose to accept that evolutionary processes can be described from different viewpoints. Which level of description we should choose depends on the given subject and interest. In this paper, we take ⟨*genotype*, *individual organism*, *species*⟩ as an appropriate triple for description of the biological evolution.

In evolutionary biology, N. Eldredge and S. J. Gould proposed the *theory of punctuated equilibrium*, which is an alternative to Darwin's *phyletic gradualism* (Eldredge and Gould 1972). In describing the history of evolution, Gould took environmental change seriously. According to this view, the evolutionary biology cannot be a closed discipline, because organisms live in an environment that stands in causal interactions with other natural entities. Thus, a radical change in the environment, such as an extraterrestrial impact or a massive bout of volcanism, might affect evolutionary processes.

This view can be combined with ideas of *co-evolution* and *niche constructions*. The main idea goes back to Lewontin (1983). Lewontin described the fundamental principle of the standard evolutionary theory as follows:

$dO/dt = f_1(O, E).$

$dE/dt = g_1(E).$

In these equations, O, E, dO/dt, and dE/dt represent *organisms' state*, *environmental state*, *evolutionary change of organisms* and the *environmental change*, respectively. According to these equations, the evolutionary change is assumed to depend on both organisms' states and environmental states, but environmental change is assumed to depend on environmental states only. Lewontin proposed a new interpretation of the environmental change and expressed it through the following equations:

$dO/dt = f_1(O, E).$

$dE/dt = g_2(O, E).$

According to these equations, the environmental change also depends on the environment-modifying activities of organisms which are called *niche constructions* by Odling-Smee *et al* (2003). Then, evolutionary processes can be described as co-evolution between organisms and their environment. Note

[*1] For details of discussions, see Lloyd (2012).

that $dE/dt = g_2(O, E)$ is more general than $dE/dt = g_1(E)$. The latter equation is a special case of the former equation in which the environment-modifying activities of organisms have no influence on the environmental state.

1.2 Evolutionary approaches in the philosophy of science

In the philosophy of science, there have already been several approaches that include evolutionary thought as a crucial element. For example, van Fraassen (1980) defended his anti-realistic position by using an idea of evolution (Chapter 2). To explain the success of current scientific theories, an evolutionary idea can be used. All current scientific theories are theories that have survived intense competition among different kinds of scientific activities. The theories that have survived are usually more accurate and more powerful than the extinct theories. The evolutionary concept is attractive especially for philosophers who reject a dogmatic type of scientific realism that explains the success of scientific activities through a continuous approach to the truth. The last paragraph of Kuhn (1962/1970) sketches the evolution in science exactly in this line: "The developmental process described in this essay has been a process of evolution *from* primitive beginnings – a process whose successive stages are characterized by an increasingly detailed and refined understanding of nature. But nothing that has been or will be said makes it a process of evolution *toward* anything." (p. 170f) In principle, our approach in this paper agrees with this remark of Kuhn.

As some philosophers pointed out, the *theory of punctuated equilibrium* in evolutionary biology supports Kuhn's dynamic description of scientific activities (Giere 1999, p. 48; Nickles 2013, Section 3.4). Kuhn (1962/1970) distinguished two developmental phases in science and called them *normal science* and *scientific revolution*. In a phase of normal science, knowledge in a discipline continuously increases. In a phase of scientific revolution, there is a radical change in the discipline and researchers radically change their views, their basic beliefs, and their methodological principles.

In the 1990s, *incommensurability* and *evolution* became the core notions of Kuhn's philosophy of science (Kuhn 2000). Kuhn said: "After a revolution there are usually (perhaps always) more cognitive specialties or fields of knowledge than there were before. Either a new branch has split off from the parent trunk, as scientific specialties have repeatedly split off in the past from philosophy and from medicine. Or else a new specialty has been born at an area of apparent overlap between two preexisting specialties, as occurred, for example, in the cases of physical chemistry and molecular biology." (Kuhn 2000, p. 97)[*2] Kuhn (2000) sometimes mentioned a strong similarity between the biological evolution and the scientific development. It is one of the aims of this paper to illustrate an evolutionary description of scientific and technological activities.[*3]

[*2] This evolutionary view of Kuhn (2000) was pointed out by one of the reviewers.

[*3] D. Hull (1988) proposed an evolutionary theory of science that is based on the social structure of science and its reward

2 Evolutionary theory for science and technology

What is the unit of the evolution of science and technology? We propose a triple ⟨*theory structure*, *research team*, *research school*⟩ as the unit of the scientific evolution. R. Dawkins (1976) introduced the notions of *replicator* and *vehicle* into evolutionary biology. By doing so, he generalized the *selection process* as a notion that can also be used outside of biology. In biology, genes represent *replicators* and organisms in an environment represent *vehicles*. D. Hull (1980) proposed to replace the term *vehicle* by *interactor* and stated that the replicator and interactor roles are fundamental to any evolutionary process (Godfrey-Smith 2010). If this view is right and it is legitimate to talk about scientific evolutions, then it is natural to assume that we can find *replicators* and *interactors* also with respect to scientific evolutions. Indeed, this is the case. Theory structures represent replicators and research teams represent interactors. Parts of a theory structure are inherited from an old research team to a new one. In every moment, all research teams try to solve some problems in their discipline based on their own theory structures. In this trial, some of them succeed in extending or refining old theory structures. Then again, the refined theory structures are inherited to the next research teams. This kind of continuing process corresponds to scientific activities that are called *puzzle-solving* in Kuhn (1962/1970).

2.1 Theory structures

A theory structure is the first component of the complex unit of the scientific evolution. It is a linearly ordered set of sets of sentences. The order in a theory structure expresses researcher's subjective evaluation about the fundamentality of sets of sentences. A theory structure is a part of an individual belief structure and it can be shared by many researchers. In Section 3.2, we define the notion of *theory structure* in detail.

Our approach in this paper is based on *Logic of belief structures* (LBS) proposed in Nakayama (2015a). This approach belongs to a tradition that is related with Quine's holism (Quine 1953) and the principle of minimal belief change. The standard formulation of belief change in this line was proposed by C. Alchourrón, P. Gärdenfors, and D. Makinson (Gärdenfors 1988) and was called *AGM-model*. This approach represents a belief state of an agent by a deductively closed belief set. Nakayama (2015a) defined a belief structure *BS* in the first step and defined a deductive closure of a consistent substructure of *BS* in the second step. Furthermore, Nakayama (2015a) showed that the semantics with sphere systems proposed by Lewis (1973) holds in LBS.

There is a different type of formal approach for theory change. It is an approach proposed by J. Sneed (1971) and extended by Balzer *et al* (1987). This approach is based on a model-theoretic representation: ″The fundamental intuition underlying our approach is that the smallest significant or interesting parts of empirical science – things like empirical laws – are best characterized, not as linguistic entities, but as

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system (Godfrey-Smith 2010). These are aspects that our paper does not deal with. The topic remains as our future task.

model-theoretic entities – classes of set-theoretic structures″ (Balzer *et al* 1987, p. xxi). In Chapter 5, they show how to deal with the ″normal″ evolution of science. However, this approach faces two problems:

(1a) It is difficult to apply this method to theories that are not mathematically described.

(1b) It is difficult to deal with *radical* theory changes within this approach. This is because an acceptance of new information might produce an inconsistency in an accepted theory, when it is radically changed.

With respect to these points, our approach, which is based on belief structures, is more general and flexible than this structuralist approach.

2.2 Research teams

A research team is the second component of the unit of the scientific evolution. It is a group of scientists who share the same theory structure and the same research goal. A research team in our sense includes not only researchers but also observation devices and experimental equipments that are used by these researchers in the team. We interpret a research team as an *extended agent* in the sense defined in Nakayama (2013, 2015b). The definition presupposes the four-dimensional mereology[*4] proposed in Nakayama (1999, 2009).

Definition1.

(2a) [Atomic Agent] An atomic agent is an agent. Any spatial part of an atomic agent is no agent. Here, we simply presuppose that there are atomic agents. An atomic agent constitutes the core (or one of the cores) of any extended agent.

(2b) [Agents and Tools] Let *temporal-part* (x, t) denote the temporal part of object x in time t. Let A be an agent that uses (tool) B in time t to perform an action. Then, the (four-dimensional) mereological sum, *temporal-part* (A, t) + *temporal-part* (B, t)**,** is an agent. By the way, we can easily prove within the four-dimensional mereology that *temporal-part* (A+B, t) = *temporal-part* (A, t) + *temporal-part* (B, t).

(2c) [Collective Agent] If agents $A_1, \ldots, A_n$ perform a *joint action*[*5], then $A_1 + \ldots + A_n$ is an agent.

(2d) If an object satisfies neither (2a) nor (2b) nor (2c), then it is no agent.

(2e) [Extended Agent] An agent that is not atomic is called an *extended agent*.

This interpretation of a *research team* as an extended agent plays an important role in ETST. In the

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[*4] For *four-dimensionalism*, see Sider (2001). For *mereology*, see Varzi (2016).

[*5] For the notion of *joint action,* see Tuomela (2002).

history of science, the development of observation devices has often influenced the selection process of research schools. For example, Galileo's observation of celestial bodies with a telescope provided new observation data in astronomy and he demonstrated how these data were incompatible with the Aristotelian Cosmology. Here, we can consider ⟨Galileo + his telescope⟩ as an extended agent. In this example, we can see that scientific activities might be dependent on the availability of technological devices. On the one hand, the development of technological devices often depends on the development of sciences. For example, the design of computers was made possible by the theoretical development of Turing machines in mathematics; the production of semiconductors is enabled by the development of quantum physics. On the other hand, in many scientific disciplines, experiments are only possible with the help of complex technical devices: the discovery of the neutrino oscillations by a research team equipped with the Super-Kamiokande[*6] is a typical example. This discovery suggests that neutrino has a mass, which denies a prediction based on the Standard Model of particle physics. In this way, experimental results obtained by the use of technological devices can influence the development of scientific theories. This co-evolution of science and technology can be appropriately described by using Lewontin's equation (See Section 1.1 of this paper).

We modify Lewontin's equation as follows: $dS/dt = f_S(S, E)$, $dE/dt = g_S(S, h(T, E))$, $dT/dt = f_T(T, E)$, $dE/dt = g_T(T, h(S, E))$. We assume that scientific development has a positive effect on the technological development and vice versa. Thus, $dS/dt > 0$ and $dT/dt > 0$. Then, it holds for $t_1, \ldots, t_4$ be with $t_1 < t_2 < t_3 < t_4$:

$$S(t_2) = S(t_1) + f_S(S(t_1), E(t_1))(t_2 - t_1),\ E(t_3) = E(t_2) + g_S(S(t_2), h(T(t_2), E(t_2))(t_3 - t_2),$$
$$T(t_4) = T(t_3) + f_T(T(t_3), E(t_3))(t_4 - t_3),\ E(t_5) = E(t_4) + g_T(T(t_4), h(S(t_4), E(t_4))(t_5 - t_4).$$

Then, we obtain: $S(t_1) < S(t_2)$ and $T(t_3) < T(t_4)$. In other words, science and technology have mutual positive feedbacks, so that they positively influence each other.[*7]

When the conditions, $dS/dt > 0$ and $dT/dt > 0$, are fulfilled for a certain period and $t_1, \ldots, t_n$ belong to this period, it holds: $S(t_1) < S(t_2) < S(t_5) < S(t_6) < \ldots < S(t_{n-2})$ and $T(t_3) < T(t_4) < T(t_7) < T(t_8) < \ldots < T(t_n)$. Note that this kind of progress in science and technology depends on the property of environment $E(t)$ in this period. Furthermore, the environment $E(t)$ can be influenced by social and natural resources. In fact, the co-evolution in the recent three centuries deals with the economic growth of the countries in which leading researchers performed their scientific activities. Since the Industrial Revolution in the 18th century, industrial capitalism has been continuously developed. This economic condition of the world is one of

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[*6] Super-Kamiokande is the large water Cherenkov detector located in Gifu prefecture, Japan.

[*7] We can describe the development of technological devices as a case of the evolution of artificial kinds. In this paper, we do not discuss this topic for want of space.

reasons for the continuous progress of science and technology after the Industrial Revolution.

2.3 Research schools

A research school is the third component of the unit of the scientific evolution. Members of a research school share the same theory structure. Like species, some new scientific traditions emerged and some became extinct during history. For example, a research school of Newtonian Mechanics emerged in the 17th century. In the same period, the school of Ptolemic Astronomy became finally extinct.

M. Ghiselin suggested that biological species might be best seen not as kinds but as individuals: "'Species' may be defined as *the most extensive units in the natural economy such that reproductive competition occurs among their parts*" (Ghiselin 1974, p. 536). Similarly, we propose to interpret a research school as an individual, or more precisely as a four-dimensional entity composed of historically extended research teams. Note that we have already proposed to consider a research team as a kind of four-dimensional entity, namely as an extended agent. Thus, this ontological proposal for research schools is consistent with our ontological position. In case of biology, Ghiselin proposed reproducibility among organisms in a species as an essential criterion for the range of the species. In science, we might use commensurability as a criterion for the range of a research school.

Kuhn (1960/1972, 2000) dealt with problems of incommensurability. A research school can be seen as a commensurable unit in which researchers can develop their own scientific ideas and cite results of other researchers in order to solve their own problems. In contrast, among incommensurable research schools[*8], there are communication difficulties. They contend against each other, and only some of them can survive.

A scientific discipline can be considered as a four-dimensional mereological sum of research teams. However, we use the notion of *research school* in a diachronic context and that of *scientific discipline* in a synchronic context.

Note that the range of research schools depends on the choice of theory structures. When we are restrictive with the choice of theory structures, the range of the corresponding research school becomes small.

2.4 Historical developments of scientific activities

We interpret the historical development of scientific activities as an evolutionary process. A theory structure corresponds to a replicator; a research team corresponds to an interactor; a research school corresponds to a species. It is notable that a theory structure is an abstract entity and it does not exist in the real world. In contrast, research teams are real objects in the world. Thus, a theory structure can obtain a

[*8] In this paper, we stipulate *incommensurable research schools* as follows: two research schools are incommensurable iff (if and only if) the theory structures they accept are mutually inconsistent. In this paper, we use *iff* as an abbreviation of *if and only if*.

meaning in reality, only if it is shared by research teams.

Theory structures have also a historical dimension. Students and researchers learn a theory structure through lectures or papers or books or other representations. A theory structure can be conveyed from a person to another. This procedure of the inheritance of theory structures is similar to the inheritance of genotypes. However, this evolutionary process is not Darwinian but Lamarckian; it permits inheritances of acquired characters. When a researcher, or a research team, proposes a change to an established theory structure, other researchers decide whether they accept this change or not. In this decision, they use some criteria for acceptance of theory structures. In Section 4 of this paper, we discuss these criteria in more detail.

The theory structure that characterizes a research school is a part of theory structures that are shared by all research teams in it. In other words, theory structures of research teams in a research school might be slightly different. In a phase of Kuhnian normal science, the theory structure of a research school is continuously extended. In a phase of Kuhnian revolution, a theory structure that is inconsistent with the theory structure of the established research school is proposed and extended, so that a new research school becomes influential (See Section 4.2 of this paper).

3 Theory structures

A theory structure can be shared by many researchers in a discipline. In other words, it can be a part of their belief structures.

3.1 Logic of belief structures

Before introducing theory structures, we need to represent individual epistemic states. To do so, we use a representation of belief structures proposed by Nakayama (2015a). A belief structure is a linearly ordered set of consistent sets of FO-sentences (First-order sentences)[*9]. In this section, we define a logical framework for such belief structures and call it *Logic of Belief Structures* (LBS).[*10]

Definition 2. Let $cons(T)$ mean that T is consistent.[*11]

(3a) [Belief structure BS] $BS = \langle ST, > \rangle$ is a *belief structure*, when the following three conditions are satisfied:

[1] $ST = \{T_i : 1 \leq i \leq n \ \& \ T_i$ is a consistent set of FO-sentences$\}$,

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[*9] First-order sentences are sentences of *First-order Logic* (FOL).

[*10] LBS is based on *Logic of Epistemic Modalities* (LEM). LEM can be combined with normative inferences (Nakayama 2015c). Nakayama (2014, 2016) propose such logical frameworks, namely Logic for Normative Systems (LNS) and Dynamic Normative Logic (DNL). Nakayama (2015a) investigates modalities in English based on LEM and LNS.

[*11] We define *consistency* as usual: T is consistent iff T entails no contradiction. Formally: T is consistent iff $p \wedge \neg p$ does not follow from T.

[2] $>$ is a total order[*12] on ST and $T_1 > \ldots > T_n$, and

[3] for all $T_i \in ST$ and $T_j \in ST$, $T_i \cap T_j = \varnothing$.

(3b) [k first fragment of BS] $top(BS, k) = \cup\{T_i : 1 \leq i \leq k \text{ and } T_i \in ST\}$. In other words, *k first fragment of BS* is the union of the first k elements of BS. We can also define $top(BS, k)$ recursively as follows:

[1] $top(BS, 1) = T_1$.

[2] $top(BS, k) = top(BS, k - 1) \cup T_k$.

(3c) [Consistent maximum of BS] $top(BS, k)$ is the *consistent maximum of BS* (abbreviated as $cons\text{-}max(BS)$) iff ($cons(top(BS, k))$ & *not* $cons(top(BS, k+1))$). We call k the *consistent maximum number of BS* (abbreviated as $cmn(BS)$), when $top(BS, k) = cons\text{-}max(BS)$.

(3d) [Deductive closure] $Cn(T) = \{p : p$ deductively follows from $T\}$.

(3e) [Belief set for BS] We call $Cn(cons\text{-}max(BS))$ the *belief set for BS*.

The relation $>$ expresses the reliability order over ST. $T_i > T_j$ means: T_i is *more reliable* than T_j. We can divide a belief structure BS into two parts, namely the *consistent part*, $top(BS, k)$ with $k \leq cmn(BS)$, and the *inconsistent part*, $top(BS, k)$ with $cmn(BS) < k \leq n$. Now, let us define the *belief structure revision* and *expansion*.

Definition 3. Let H be a consistent set of FO-sentences. Let BS be a belief structure with $T_1 > \ldots > T_n$.

(4a) We define $ext(H, BS)$ as the belief structure with $H > T_1 > \ldots > T_n$. In other words, the extended belief structure of BS by H is the belief structure that can be obtained from BS by adding H as the most reliable element.

(4b) [Belief structure revision] $bsR(BS,H) = Cn(cons\text{-}max(ext(H, BS)))$.

(4c) [Belief structure expansion] $bsEX(BS, H) = Cn(cons\text{-}max(BS) \cup H)$.

We can show that our revision operator bsR satisfies all of postulates for the belief revision operator in AGM-model[*13], if $H = \{p\}$ and p is a consistent FO-sentence.[*14] The AGM-model is a theory for propositional representation and our revision operator is defined for FO-sentences. In this sense, our approach is broader than the AGM approach.

[*12] Thus, $>$ is irreflexive, transitive, and total.

[*13] AGM-model is widely accepted as the standard theory for belief revision. For AGM-model, see Gärdenfors (1988, Section 3.3) and Hansson (2014).

[*14] The proof of this claim can be found in Nakayama (2015a).

3.2 Characterizations of theory structures

We define the notion of *part of belief structures* as follows.

Definition 4.
(5a) Let $BS_a = \langle ST_a, >_a \rangle$ be a belief structure with $A_1 >_a \ldots >_a A_n$ and $BS_b = \langle ST_b, >_b \rangle$ be a belief structure with $B_1 >_b \ldots >_b B_m$.

BS_b is a part of BS_a iff

[1] for every X in ST_b, X is an element of ST_a and

[2] for every X and Y in ST_b, if $X >_b Y$, then $X >_a Y$.

(5b) Let $TS = \langle ST, > \rangle$. Let BS_x be a belief structure that person x has.

Belief structure TS is shared by *TEAM* iff for every member x of *TEAM*, TS is a part of BS_x and $\cup ST$ is a subset of *cons-max*(BS_x).

Theory structures belong to consistent belief structures. In other words, we require the following features from theory structures.

Definition 5. Let $TS = \langle ST, > \rangle$.

TS is is a theory structure iff

[1] TS is a belief structure,

[2] TS is consistent, namely $\cup ST$ is consistent, and

[3] TS is shared by multiple persons.

According to Definition 5, a theory structure is a consistent belief structure that is shared by multiple persons. What students learn from lectures and books builds components of their belief structures. They also learn which parts of a theory structure are more important than others. In short, good students learn the theory structure in a scientific discipline that is accepted by most researchers in that discipline. After some work, the theory structure becomes a consistent part of their belief structures. When researchers are successful, they can add new findings to the standard theory structure. In this way, a theory structure grows thorough activities of researchers.

3.3 Theory structures and scientific research programs

I. Lakatos (1978) proposed a theory for theory changes and introduced the notion of *scientific research programs* (*RP*). Lakatos divided theoretical assumptions in science into two parts, namely *hard core* and *auxiliary hypotheses*. The hard core of a *RP* can be protected against anomalies by replacing its old auxiliary hypotheses with new ones. In this way, a *RP* can be enriched so that it has more explanatory and predictive power than before. In such a successful case, the *RP* is characterized as *progressive*. Otherwise, a *RP* is *degenerative*. This explanation can be also described in terms of *series of theories.*

> "Let us take a series of theories, T_1, T_2, T_3,… where each subsequent theory results from adding auxiliary clauses to (or from semantical reinterpretations of) the previous theory in order to accommodate some anomaly, each theory having at least as much content as the unrefuted content of its predecessor. Let us say that such a series of theories is *theoretically progressive* (*or* '*constitutes a theoretically progressive problemshift*') if each new theory has some excess empirical content over its predecessor, that is, if it predicts some novel, hitherto unexpected fact. Let us say that a theoretically progressive series of theories is also *empirically progressive* (*or* '*constitutes an empirically progressive problemshift*') if some of this excess empirical content is also corroborated, that is, if each new theory leads us to the actual discovery of some *new fact*. Finally, let us call a problemshift *progressive* if it is both theoretically and empirically progressive, and *degenerating* if it is not." (Lakatos 1978, p. 33f)

This Lakastos' idea can be easily formulated in LBS. Let us assume that there is a theory structure $TS_k = \langle ST_k, >\rangle$ such that $ST_k = \{T_1,\ldots, T_k\}$ and any member of ST_k is a theory of the same scientific discipline. Then, we can easily prove: If for any n and m with $m < n \leq k$, [$ST_m \subseteq ST_n$ and an empirical sentence is a member of $Cn(\bigcup ST_n) - Cn(\bigcup ST_m)$], then for any n with $n \leq k$, TS_n is theoretically progressive. We can also show: If for any n and m with $m < n \leq k$, [$ST_m \subseteq ST_n$ and there is a corroborated empirical sentence in $Cn(\bigcup ST_n) - Cn(\bigcup ST_m)$], then for any n with $n \leq k$, TS_n is empirically progressive.

A theory structure has a fine structure and can explain some central features of *RP*s. We can easily prove the following proposition that explains some aspects of theory change.

Proposition 6. Let *CT* be a hard core of a research program. Let $oa(CT)$ and $na(CT)$ be the old and the new auxiliary hypotheses for *CT*, respectively. Let *oOD* and *nOD* be the old and the new observation data, respectively. We assume that $CT \cup oOD \cup oa(CT)$ and $CT \cup oOD \cup nOD \cup na(CT)$ are consistent and that $CT \cup nOD \cup oa(CT)$ is inconsistent. Let $BS_{old} = \langle\{CT, oOD, oa(CT)\}, >_{old}\rangle$ with $CT >_{old} oOD >_{old} oa(CT)$ and $BS_{new} = \langle\{CT, oOD, na(CT)\}, >_{new}\rangle$ with $CT >_{new} oOD >_{new} na(CT)$.

(6a) For every sentence p in CT, p is in $bsR(BS_{new}, nOD)$.

(6b) There is a sentence p in $oa(CT)$ such that p is not in $bsR(BS_{old}, nOD)$.

Proof. Because $CT \cup oOD \cup nOD \cup na(CT)$ is consistent, $bsR(BS_{new}, nOD) = Cn(nOD \cup CT \cup oOD \cup na(CT))$. Thus, $CT \subseteq bsR(BS_{new}, nOD)$. Hence, (6a) holds. Now, note that $bsR(BS_{old}, nOD) = Cn(nOD \cup CT \cup oOD)$, because $CT \cup oOD \cup nOD$ is consistent, $CT \cup nOD \cup oa(CT)$ is inconsistent, and

$CT >_{old} oOD >_{old} oa(CT)$. To show (6b), suppose that every sentence in $oa(CT)$ is in $bsR(BS_{old}, nOD)$. But, this contradicts to inconsistency of $CT \cup nOD \cup oa(CT)$. Thus, (6b) holds. Q.E.D.

According to (6a), every element of the hard core of *RP* remains as an element of the hard core of the revised *RP* after the update by new observation data. Additionally, (6b) shows that some parts of the old auxiliary hypotheses are not acceptable after the update.

We can imagine a series of theory changes that can be described as $CT \cup oa(CT)$, $CT \cup n_1a(CT)$, $CT \cup n_2a(CT)$, and so on. When the explanatory power of the new construction is more than the older one, the research program with the hard core *CT* is progressive. However, a conflict might occur, when $CT \cup na(CT)$ explains only new data but not a significant part of the old data. This corresponds to the situation that Kuhn described as a crisis (Kuhn 1962/1970).

Compared to Kuhn's approach, Lakastos' approach is more precise. However, it is too restrictive and has some problems. Here, we summarize six problems of Lakastos' approach that are appropriately pointed out by Laudan (1977, p. 77f):

(7a) As with Kuhn, Lakastos' conception of progress is exclusively empirical; the only progressive modifications in a theory are those which increase the scope of its empirical claims.

(7b) The sorts of changes which Lakatos allows within the mini-theories which constitute his research program are extremely restricted.

(7c) A fatal flaw in the Lakatosian notion of research programs is its dependence upon the Tarski-Popper notions of "empirical and logical content".

(7d) Because of Lakastos' idiosyncratic view that the acceptance of theories can scarcely if ever be rational, he cannot translate his assessments of progress into recommendations about cognitive action.

(7e) Lakastos' claim that the accumulation of anomalies has no bearing on the appraisal of a research program is massively refuted by the history of science.

(7f) Lakastos' research programs, like Kuhn's paradigms, are rigid in their hard-core structure and admit of no fundamental changes.

Point (7a) is related with Laudan's distinction between conceptual and empirical problems. Laudan (1977) characterized conceptual problems as follows:

"Conceptual problems arise for a theory, *T*, in one of two ways:

1. When *T* exhibits certain internal inconsistencies, or when its basic categories of analysis are vague and unclear; these are *internal conceptual problems*.

2. When T is in conflict with another theory or doctrine, T', which proponents of T believe to be rationally well founded; these are *external conceptual problems*." (p. 48f)

However, Kuhn and Lakatos do not respect conceptual problems. In this paper, we interpret these conceptual problems as problems of (internal and external) *coherence* (See Section 4 of this paper). As Laudan pointed out, Lakastos' evaluation criteria are too restrictive. We need more general formulation of *research programs* and more general evaluation criteria. We have shown that theory structures can be used to describe patterns of scientific research programs. However, theory structures can be also used to describe more complex developments of scientific activities. We propose general evaluation criteria in Section 4.

3.4 Observations and theories

Let us apply LBS to analysis of the relationship between observations and theories. Both logical positivists and K. R. Popper tended to see a direct relation between observation data and scientific theories. Let us consider the sentence "All ravens are black" as an example. Here, we assume that this sentence is a single component of theory T. The set OD of observation data consists of sentences that report whether each of observed ravens is black or not. Both logical positivists and Popper tended to assume that observation data are veridical, because they are obtained by direct experience. This situation can be represented as $OD > T$. In general, there are at least three relations between OD and T.

(8a) [Confirmation] OD (deductively) follows from T.

(8b) [Compatibility] The union of T and OD is consistent. Namely, $cons(T \cup OD)$.

(8c) [Falsification] The union of T and OD is inconsistent. Namely, *not* $(cons(T \cup OD))$.

The confirmation characterized by (8a) does not exclude the future possibility of falsification, because it is still possible that we gain a new observation result expressed by p such that the union of T and OD and {p} is inconsistent. This is a point made by Popper against the logical positivism (Popper 1934, 1959).

Note that OD falsifies T, only if OD is more reliable than T (i.e., $OD > T$). If T is more reliable than OD (i.e., $T > OD$) and $T \cup OD$ is inconsistent, then OD is falsified by T. In this latter case, people still believe in T and try to reject observation data OD.

As N. R. Hanson indicated, scientific observations are normally *theory-laden* (Hanson 1958). To make scientific observations, scientists need theoretical and practical education. As a result, direct observations OB are not identical with observation data OD. Now, we interpret OD as the set of sentences that are inferred from a particular observation theory OT and the set OB of direct observations. In such a case, we should accept: $OB > OT > OD$. When OD is more reliable than T (thus, $OB > OT > OD > T$), we have two different types of possibilities, namely (8d) and (8e).[*15]

(8d) [Accurate values] Any element of *OD* can be quite precisely predicted by *T* (with the help of certain assumptions).

(8e) [Inaccurate values] Some elements of *OD* greatly differ from the values predicted by *T* (even with the help of certain assumptions).

However, in this case, the option $T > OT$ (thus, $OB > T > OT > OD$), is also available. This means that researchers may criticize the observation theory *OT*, to keep the theory *T* intact. A similar argumentation was made by Lakatos to criticize the *dogmatic falsificationism* (Lakatos 1978, p. 14f). Here, we tried to clarify his argumentation within LBS.

4 Acceptance criteria and their applications

There are some epistemic values that researchers use to evaluate theory structures. Among these values, we focus on three, namely *accuracy*, *expressibility*, and *coherence*. Researchers use these values in order to decide which theory structure they accept.

4.1 Criteria for acceptance of theory structures

Scientific realists characterize the goal of scientific activities as the *truth*. However, there is a more neutral expression of this goal, namely *accuracy*. The accuracy of descriptions or predictions can be determined without knowing the truth. When we have a set of correct experimental data, we can compare predictions from two competing theories with them and decide which of them provides more accurate predictions. In this comparison, we need not to know whether these theories are true or not.

Research schools have developed their own special languages. In some cases, these languages contain mathematical expressions or equations. Experts in a discipline communicate to each other in this special language. Thus, students in a research school have to learn the special language used in it.

In some cases, a theory T_1 can have more technical terms than T_2 and anything that is expressible in T_2 is also expressible in T_1. In such a case, we say that T_1 is more expressible than T_2. This *expressibility* of the special language in a research school can be considered as a sign of its development. Sometimes, special terms and theories are developed, so that a new discipline branches from a traditional discipline. The internal *coherence* indicates the connectedness among elements of a theory structure.

When researchers select a theory structure, they use some epistemic values. In this paper, we pick up three epistemic values, namely *accuracy*, *expressibility*, and *coherence*. Corresponding to these viewpoints,

[*15] Here, we should distinguish predictions and observations, because a prediction sometimes presupposes simplified description of the given situation.

we introduce three types of partial orderings, namely $<_{AC}$, $<_{EX}$, and $<_{CH}$. They are irreflexive and transitive relations.[*16] We read these orderings as follows:

$TS_m <_{AC} TS_k$: TS_k is more accurate than TS_m.
$TS_m <_{EX} TS_k$: TS_k is more expressive than TS_m.
$TS_m <_{CH} TS_k$: TS_k is more coherent than TS_m.

We can characterize these orderings as follows.

Definition 7. Let $TS = \langle ST, >\rangle$.
(9a) [Theory Set] $ts(TS) = ST$. We call $ts(TS)$ the *theory set for TS*.
(9b) [Theory Base] $tb(TS) = \cup ts(TS)$. We call $tb(TS)$ the *theory base for TS*.
(9c) $TS_1,\ldots,$ and TS_k are *totally consistent* iff $tb(TS_1)\cup \ldots\cup tb(TS_k)$ is consistent.
(9d) TS_k and TS_m are *mutually inconsistent* iff $tb(TS_k)\cup tb(TS_m)$ is inconsistent.
(9e) $TS_m <_{AC} TS_k$ iff $tb(TS_k)$ provides more accurate predictions than $tb(TS_m)$.
(9f) $TS_m <_{EX} TS_k$ iff anything that can be expressed in $tb(TS_m)$ can be expressed in $tb(TS_k)$.[*17]
(9g) $TS_m <_{CH} TS_k$ iff elements of $ts(TS_k)$ share more technical terms each other than elements of $ts(TS_m)$.

All of these acceptance criteria are characterized from an internal viewpoint. Besides these criteria, we consider criteria from an external viewpoint. An external viewpoint presupposes a set of theory structures in different disciplines. When we express the presupposed set of theory structures as STS_j, we obtain three kinds of external criteria:

$TS_m <_{[AC, STSj]} TS_k$: TS_k is more accurate than TS_m with respect to STS_j.
$TS_m <_{[EX, STSj]} TS_k$: TS_k is more expressive than TS_m with respect to STS_j.
$TS_m <_{[CH, STSj]} TS_k$: TS_k is more coherent than TS_m with respect to STS_j.

We can characterize three types of partial orderings for external criteria as follows.

Definition 8. Let $union(STS_j) = \cup\{tb(TS) : TS \in STS_j\}$. We assume that $union(STS_j)$ is consistent.

[*16] Some theory structures might be not comparable with each other via these criteria. This is why we require only partial orderings for these acceptance orderings.
[*17] In ideal cases, we can formulate (9f) as follows: $TS_m <_{EX} TS_k$ iff $Cn(tb(TS_m)) \subseteq Cn(tb(TS_k))$. However, in natural sciences, formulas are often interpreted in an *approximate* manner. Thus, this strict definition of the expressibility is sometimes not adequate.

Let *cons-incons*(TS_k, TS_m, *union*(STS_j)) mean the following condition: $tb(TS_k) \cup union(STS_j)$ is consistent and $tb(TS_m) \cup union(STS_j)$ is inconsistent.

(10a) $TS_m <_{[AC, STSj]} TS_k$ iff (*bsR*(TS_k, *union*(STS_j)) provides more accurate predictions than *bsR*(TS_m, *union*(STS_j)) or *cons-incons*(TS_k, TS_m, *union*(STS_j))).

(10b) $TS_m <_{[EX, STSj]} TS_k$ iff (anything that can be expressed in *bsR*(TS_m, *union*(STS_j)) can be expressed in *bsR*(TS_k, *union*(STS_j)) or *cons-incons*(TS_k, TS_m, *union*(STS_j))).

(10c) $TS_m <_{[CH, STSj]} TS_k$ iff (*tb*(TS_k) shares more technical terms with *union*(STS_j) than *tb*(TS_m) does or *cons-incons*(TS_k, TS_m, *union*(STS_j))).

We restrict here the application of the external criteria to consistent theoretical assumptions.

In sum, we can combine three criteria with two views. As a result, we obtain six criteria for evaluation of theory structures.[*18] Note that these criteria are used by researchers to evaluate different approaches in their research area. Normally, all members in a research team agree which component of criteria is the most important.

4.2 The progress in scientific disciplines

According to our view, scientific activities emerged, when researchers started to evaluate theory structures by six criteria introduced in Section 4.1. Before that time, there was no significant progress in activities of researchers, even if there might have been constructions and inheritances of theory structures.

As Kuhn (1962/1970) pointed out, the scientific knowledge is not monotonically increasing. Indeed, it is not always the case: $t1 < t2 \Rightarrow ts(SK_{t1}) \subseteq ts(SK_{t2})$.[*19] However, in this paper, we have shown that there are many time intervals $t1$ and $t2$ such that [$t1 < t2$ & SK_{t2} is more accurate than SK_{t1} & SK_{t2} is more expressible than SK_{t1} & SK_{t2} is more coherent than SK_{t1}]. In this sense, the science makes progress.

A period of crisis for a discipline can be characterized as a period during which the following two conditions hold:

[1] There are several competing theory structures $TS_1, \ldots, TS_n$.

[2] There is no k with $1 \le k \le n$ such that for all i with $1 \le i < k$ and $k < i \le n$:

$TS_i <_{AC} TS_k$ & $TS_i <_{EX} TS_k$ & $TS_i <_{CH} TS_k$.

Here again, we can confirm that ETST can be used to describe important features of scientific activities.

[*18] Laudan (1977) proposed a problem-solving approach and distinguished empirical and conceptual problems. His discussions of conceptual problems are related with our criterion of coherence.

[*19] Here, we assume that SK_t stands for the scientific knowledge in a time interval t.

4.3 Normal sciences, crisis, and scientific revolutions

In this section, we characterize the main idea of Kuhn (1962/1970) from our viewpoint. In the 1990s, Kuhn wanted to revise Kuhn (1962/1970) from a new viewpoint, but he passed away before finishing this project (Kuhn 2000).[*20]

According to Kuhn (1962/1970), there are three phases of development in a scientific discipline, namely a phase of *normal science*, a phase of *crisis* and a phase of *scientific revolution*. In each phase, the best strategy that a researcher should take is different. In a phase of normal science, researchers should accept the established paradigm and try to solve problems based on it. In a phase of crisis, researchers should propose new fundamental theories and examine how powerful they are. In a phase of scientific revolution, researchers should try to establish a new paradigm.

In the 1960s, philosophers criticized Kuhn from different viewpoints (Lakatos and Musgrave 1970). One of the most influential criticisms was made by Masterman (1970); she persuasively pointed out that Kuhn's key concept *paradigm* is too vague. This is certainly right. In this section, we clarify the main approach in Kuhn (1962/1970) by using notions introduced in this paper.

(11a) A discipline is in a phase of *normal science* iff there is a theory structure *TS* that is shared by all research schools in the discipline and there are many extensions of *TS* that are totally consistent.

(11b) A discipline is in a phase of *crisis* iff there are some theory structures that are shared by some research schools in the discipline and they are mutually inconsistent.

(11c) A discipline is in a phase of *scientific revolution* iff there are two theory structures TS_{old} and TS_{new} in the discipline such that [TS_{old} and TS_{new} are mutually inconsistent and TS_{new} is (internally) more accurate, more expressive, and more coherent than TS_{old}].

In a phase of normal science, a specialization can occur. This means that there are many extensions of the fundamental theory structure *TS* such that most of them are totally consistent. Figure 1 shows a phase of normal science in which three new special research areas branched from the original one. In this case, there are four theory structures TS_1, TS_2, TS_3, TS_4 which are totally consistent and share some part structures.[*21] The branching of a theory structure reflects a specialization process that is caused by the development of research activities.

In a phase of crisis, many research teams propose their own theory structures, which are mutually

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[*20] Kuhn died in 1996.

[*21] For example: TS_1 has a structure: $T_1 > T_2 > T_{3a} > T_{4a} > T_{5a}$, TS_2 has a structure: $T_1 > T_2 > T_{3a} > T_{4a} > T_{5b}$, TS_3 has a structure: $T_1 > T_2 > T_3 > T_4 > T_{5c}$, *and* TS_4 has a structure: $T_1 > T_2 > T_3 > T_4 > T_5$. These four theory structures share the fundamental theory structure: $T_1 > T_2$.

inconsistent (Figure 2). In this phase, many fundamental theories are proposed and examined if they can solve some anomalies of the old theory structure. However, despite their efforts, researchers cannot find any promising theory structure for a while.

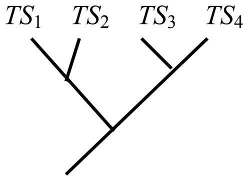

Figure 1. A dendrogram of normal science

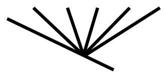

Figure 2.A dendrogram of crisis

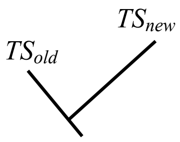

Figure 3. A dendrogram of scientific revolution

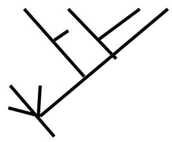

Figure 4. A dendrogram of a general development

In a phase of scientific revolution, a new theory structure is constructed that is inconsistent with the old one and researchers in a discipline come to the conclusion that the new one is better than the old one. At this stage, researchers use three epistemic values, namely three (internal) acceptance criteria. The old theory structure loses support by research teams and becomes extinct (See Figure 3). Contrary to Kuhn (1962/1970), we accept that the new theory structure may share a part structure with the old one. Thus, a new theory structure usually inherit some part of an old one. Therefore, there is a certain continuity between the new and the old theory structure. We explain the incommensurability of both theory structures solely through their mutual inconsistency.

Figure 4 combines Figure 1, 2, and 3. It demonstrates a general development schema of scientific activities. The diagram suggests a *fractal structure* of the scientific development. You may find, even within a phase of normal science, many phases of *small scientific revolutions*. In fact, we can find Kuhn's remark on *small revolutions* in the postscript of Kuhn (1962/1970).

> ″Partly because of the examples I have chosen and partly because of vagueness about the nature and size of the relevant communities, a few readers of this book have concluded that my concern is primarily or exclusively with major revolutions such as those associated with Copernicus, Newton, Darwin, or Einstein. A clearer delineation of community structure should, however, help to enforce the rather different impression I have tried to create. A revolution is for me a special sort of change involving a certain sort of reconstruction of group commitments. But it need not be a large change, nor

need it seem revolutionary to those outside a single community, consisting perhaps of fewer than twenty-five people. It is just because this type of change, little recognized or discussed in the literature of the philosophy of science, occurs so regularly on this smaller scale that revolutionary, as against cumulative, change so badly needs to be understood.″ (p. 180f)

This view is perfectly in accordance with our position. The consideration in this section shows that three phases of the scientific development described in Kuhn (1960/1970) can be explicated in a precise manner within ETST.

5 Historical examples

In this section, we apply ETST to some concrete examples. The *similarity* is not a transitive relation. We can confirm this fact also in the history of science. The similarity of theory structures is not transitive. A series of continuous changes can end with a radical change in total.

5.1 Observation data and technological developments

A technological state might belong to the environmental state for scientific activities, because researchers can use available technologies for their research activities.[*22] Contrarily, a scientific state might belong to the environmental state for technological activities, because engineers can use available scientific theories to develop new apparatuses. Thus, both types of activities can co-evolve in the sense of Lewontin (see Section 2.2).

Observation data with high quality are often obtained after a development of new technologies. Let us take an example of the invention of telescopes. It is said that the first telescope was invented by Hans Lippershey in 1608. Galileo Galilei (1564 - 1642) obtained this information, built some telescopes in 1609, started with his astronomical observations, and published *The Starry Messenger* in 1610. In this book, Galileo provided sketches of the surface of the moon and that of four moons of Jupiter. In *Letter of Sunspots* (1612), Galileo reported that the sun had spots and rotated in circular motion. More importantly, he discovered that Venus had phases just like the moon (Machamer 2014). All of these observations were made possible with the help of a telescope.

In 1663, James Gregory (1638 – 1675) proposed an idea of reflecting telescopes. Around 1670, modifying Gregory's idea, Isac Newton (1642 - 1726) invented a Newtonian reflecting telescope. This invention was motivated by his research on optics using prisms since 1666. It was one of the conclusions of Newton's research that the lens of any refracting telescope would suffer from the dispersion of light into colors. To avoid this problem, Newton constructed a Newtonian reflecting telescope that uses a concave mirror instead of an object lens. This example shows that results of scientific researches sometimes

[*22] Researchers who use technological devices can be interpreted as extended agents. See Section 2.2.

influence technological developments.

When we study the history of science, we can find, almost everywhere, technological innovations in the background of new scientific discoveries. New technologies sometimes improve the quality and the quantity of available observation data. These new observation data may reveal anomalies of the old theory structure. We can also find the reverse direction of influence, namely the influence of scientific researches on technological innovations. In this sense, the technical development and the scientific development can co-evolve.

5.2 Historical examples – Astronomy and mechanics

In this section, let us take historical examples from the 16th and the 17th century. In the beginning of the 16th century, the Aristotelian Mechanics (*AM*) and the Ptolemaic Astronomy (*PA)* were dominant.[*23] As a preparation, let us introduce some elementary statements about the universe.

(12a) The universe is finite.

(12b) The celestial realm is spherical and moves as a sphere.

(12c) The Earth is a sphere.

(12d) [Geocentrism 1] The Earth is at the center of the universe.

(12e) [Geocentrism 2] The Earth does not move.

(12f) [Geocentrism 3] There are seven planets, namely Moon, Mercury, Venus, Sun, Mars, Jupiter, and Saturn.

(12g) The planetary spheres have the following order: Moon, Mercury, Venus, Sun, Mars, Jupiter, Saturn, Sphere of fixed stars.

(12h) [*PA*-hypothesis 1] The motions of planets can be captured by using epicycles around a deferent.

(12i) [*PA*-hypothesis 2] The heavenly bodies move uniformly around an equant.

(12j) Observation data in astronomy in the 16th century.

(12k) [Heliocentrism 1] The center of the universe coincides with the center of the sun.

(12l) [Heliocentrism 2]The Earth as well as the planets move around the sun.

(12m) The moon moves around the Earth.

(12n) [Heliocentrism 3] The sphere with fix stars does not move.

(12o) [Heliocentrism 4] The Earth rotates on its axis.

(12p) The planetary spheres have the following order: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Sphere of fixed stars.

(12q) Galileo's observation data presented in *The Starry Messenger* (1610).

(12r) Tycho Brahe's data.

[*23] For the development of astronomy in the 16th century, see Rabin (2010).

(12s) [Kepler's first law] The orbit of a planet is an ellipse with the Sun in one of the foci.[*24]

(12t) [Kepler's second law] The radius vector from the Sun to a planet sweeps out equal areas.

(12u) [Kepler's third law] $(T_1/T_2)^2 = (a_1/a_2)^3$ with T_1 and T_2 representing the periodic times of two planets and $a_1$and a_2 the length of their semi-major axes.

(12v) The universe is infinite.

Note that some of these statements are incompatible. The following list shows incompatible pairs: ⟨(12a), (12v)⟩, ⟨(12b), (12s)⟩, ⟨(12d), (12k)⟩, ⟨(12e), (12l)⟩, ⟨(12e), (12o)⟩, ⟨(12g), (12p)⟩, ⟨(12h), (12s)⟩, ⟨(12n), (12v)⟩.

Now, we consider two major systems of mechanics.

(13a) [Geocentrism 1] The Earth is at the center of the universe.[*25]

(13b) The physical elements move vertically towards the center of the universe.

(13c) The celestial bodies are not physical but a fifth element whose nature is to move in perfect circles around the Earth.

(13d) [Law of inertia (the first Newtonian law)] Every body perseveres in its state of being at rest or of moving uniformly straight forward except insofar as it is compelled to change its state by forces impressed thereon.

(13e) [The second Newtonian law] A change in motion is proportional to the motive force impressed and takes place along the straight line in which that force is impressed.

(13f) [The third Newtonian law] To every action there is always opposed an equal reaction. In other words, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.

After these preparations, we begin with describing different theory structures. The following description shows a possible interpretation of theory structures of different astronomical systems.

(14a) [Theory structure of Aristotelian Astronomy: *AA*]

$\{(12a), (12b), (12c)\} >_{AA} \{(12d)\} >_{AA} \{(12e), (12f), (12g)\}$

(14b) [Theory structure of Ptolemaic Astronomy: *PA*]

$\{(12a), (12b), (12c)\} >_{PA} \{(12d)\} >_{PA} \{(12e), (12f), (12g)\} >_{PA} \{(12h), (12i)\}$

(14c) [Theory structure of Copernican Astronomy: *CA*]

$\{(12a), (12b), (12c)\} >_{CA} \{(12k)\} >_{CA} \{(12l), (12m), (12n), (12o), (12p)\} >_{CA} \{(12j)\} >_{CA}$

[*24] For Kepler's laws, see Di Liscia (2014).

[*25] (13a) is identical with (12d). This means that the Aristotelian Mechanics is dependent on the astronomical disposition.

{(12h)}

(14d) [Copernican Astronomy supported by Galileo: *GCA*][*26]

{(12a), (12b), (12c)} $>_{GCA}$ {(12l), (12m), (12n), (12o), (12p)} $>_{GCA}$ {(12j), (12q)} $>_{GCA}$ {(12h)}

(14e) [Theory structure of Keplerian Astronomy: *KA*][*27]

{(12a), (12c)} $>_{KA}$ {(12k)} $>_{KA}$ {(12l), (12m), (12n), (12o), (12p)} $>_{KA}$ {(12s), (12t), (12u)} $>_{KA}$ {(12r)}

(14f) [Theory structure of Aristotelian Mechanics: *AM*]

{(13a), (13b), (13c)}

(14g) [Theory structure of Newtonian Mechanics: *NM*]

{(13d), (13e), (13f)} $>_{NM}$ {(12v)}

(14h) [Theory structure of an astronomy based on *NM*] Let ($12c^*$) = 'The Earth is nearly a sphere'.

{(13d), (13e), (13f)} $>_{NM}$ {(12v)} $>_{NM}$ {(12s), (12t), (12u)} $>_{NM}$ {($12c^*$), (12l), (12m), (12o)}

As (14a) and (14b) show, the Ptolemaic Astronomy (*PA*) is an extension and a miner revision of the Aristotelian Astronomy (*AA*).

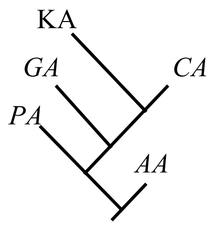

Figure 5

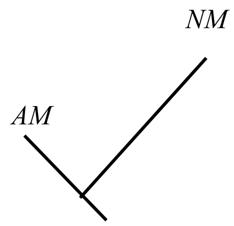

Figure 6

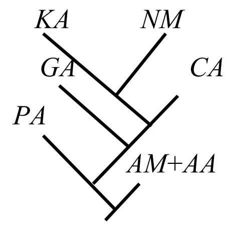

Figure 7

Figure 5 shows a dendrogram of the development of astronomy until the first half of the 17th century. Figure 6 demonstrates the development of mechanics and Figure 7 describes an interaction between astronomy and mechanics.

Now, we demonstrate how to apply acceptance criteria to the evaluation of theory structures. We assume, here, *NP* means *Neoplatonism*.

(15a) [Ptolemaic Astronomy (*PA*) and Aristotelian Astronomy (*AA*)]

[$AA <_{AC} PA$] & [$PA <_{CH} AA$] & [$PA <_{[CH,\{AM\}]} AA$].

[*26] According to Koyre (1957, p. 96), Galileo rejected the conception of a center of the universe. This means that Galileo rejected both (12d) and (12k).

[*27] The term *Keplerain Astronomy* is not often used. However, we use this term to characterize the theory structure that represents astronomical principles proposed by J. Kepler.

(15b) [Ptolemaic Astronomy (*PA*) and Copernican Astronomy (*CA*)]

$[PA <_{CH} CA]$ & $[CA <_{[CH,\{AM\}]} PA]$.

(15c) [Copernican Astronomy (*CA*) supported by Galileo]

$[GCA <_{[CH,\{AM\}]} CA]$ & [The observation data in *GCA* show that *AM* is heavily problematic].

(15d) [Keplerian Astronomy (*KA*)]

$[CA <_{AC} KA]$ & $[CA <_{EX} KA]$ & $[CA <_{CH} KA]$ & $[PA <_{AC} KA]$ & $[PA <_{EX} KA]$ & $[PA <_{CH} KA]$ & $[KA <_{[CH,\{AM\}]} PA]$ & $[PA <_{[CH,\{NP\}]} KA]$.

(15e) [Newtonian Mechanics (*NM*)]

$[AM <_{AC} NM]$ & $[AM <_{EX} NM]$ & $[AM <_{CH} NM]$ & $[PA <_{[AC,\{NM\}]} KA]$ & $[PA <_{[EX,\{NM\}]} KA]$ & $[PA <_{[CH,\{NM\}]} KA]$.

According to (15a), *PA* is more accurate than *AA* but less coherent than *AA*. Especially, motions of planets described in *PA* violate some principles of *AM*. Specialists in the European Middle Ages tended to accept *PA* only as a mathematic device and ignored its metaphysical consequences.

Nicolaus Copernicus (1473 - 1543) proposed the Copernican Astronomy (*CA*) which was a heliocentric theory (See (12k), (12l), (12o), and (14c)). It could not show any improvement from *PA* with respect to accuracy and simplicity (Kuhn 1957, Chapter 5). However, *CA* is more coherent than *PA*. As Johannes Kepler (1571-1630) pointed out, *PA*'s curious arrangement of scales of epicycles of Mars, Jupiter, and Saturn could be plausibly explained by *CA* (Dreyer 1906/1953, p. 373).

The geocentrism forms the core of the Aristotelian Mechanics (*AM*) (See (13a) and (14f)). This is why the heliocentrism of *CA* could have such strong effects in the modern history of physics. The acceptance of the heliocentrism forces astronomers to reject the central part of *AM*. In the beginning of the 17^{th} century, based on astronomical data of Tycho Brahe (1546 - 1601), Kepler succeeded in constructing a heliocentric system that was much more accurate than *PA* and *CA* (See (15d)). As a result, *PA* and *CA* lost adherents after the enunciation of the Keplerian astronomy (*KA*). Because *KA* is strongly incoherent with *AM*, there was an urgent need of a new mechanical system. *CA* still accepts a central dogma of *AM* that circular movements are essential in the celestial sphere. *KA* denies this dogma and states that orbits of planets are ellipses. While *AM* is formulated in a language of quality, *KA* describes movements of planets with mathematical equations. From these reasons, for researches who accept *KA*, *AM* appeared as a totally wrong mechanics.

Newton provided a new mechanics in his *Philosophiæ Naturalis Principia Mathematica* (1687) and derived *KA* from his Newtonian Mechanics (*NM*). (15e) shows that *NM* is superior to *AM* with respect to all internal criteria. Thus, with the publication of *NM*, *AM* totally lost its value in natural philosophy. In this way, a scientific revolution in mechanics was completed.

In the development from *CA* to *NM*, there was no persisting paradigm or no hard core of a scientific research program. In this development, *CA* played an important role, because *CA* rejected the geocentrism that was the essential part of *AM*. Additionally, *CA* proposed a heliocentric system that was as good as *PA* with respect to internal acceptance criteria. Later, a part of the heliocentric ideology was rejected through proposals of the infinite universe by Giordano Bruno (1548 - 1600) and Newton. This movement, which was started with the publication of Copernicus' book in 1543, ended with a proposal of a universal mechanics by Newton in 1687. *NM* gave a foundation of *KA* and was superior to *AM* in every respect. With the establishment of *NM*, a large part of astronomy became a sub-discipline of mechanics.

5.3 Examples for the external coherence

As we have seen in Section 5.2, the development of astronomy and mechanics can be considered as an example for the importance of the external coherence. Kepler could reject Aristotelian metaphysics, because he was a Neoplatonist. *KA* is externally coherent with the Neoplatonic metaphysics. Kepler was interested in constructing an astronomical theory that is compatible with Neoplatonism (Kuhn 1957, Chapter 6).

In this section, we shortly discuss the development of the Theory of the (General) Relativity (*TR*) in this context. It provides another example for the importance of external coherence.

A major part of the electromagnetic theory (*EM*) was developed by Michel Faraday (1791 - 1867) in the 1830s and was mathematically formalized by James C. Maxwell (1831 - 1879) in 1864. It turned out that *EM* and the Galilean transformation in *NM* is incoherent. In 1904, Hendrik A. Lorentz (1853 - 1928) proposed the Lorentz transformation in order to show how to deal with the appearance of inconsistency between *NM* and *EM*. Finally, Albert Einstein (1879 – 1955) succeeded in defining a mechanics that kept Maxwell's equation invariant with respect to different coordinate systems. We can describe this situation with the ordering of the external coherence.

(15f) [Newtonian mechanics (*NM*) and Theory of (General) Relativity (*TR*)]

$[NM <_{AC} TR]$ & $[NM <_{EX} TR]$ & $[NM <_{[AC,\{EM\}]} TR]$ &$[NM <_{[EX,\{EM\}]} TR]$ &$[NM <_{[CH,\{EM\}]} TR]$.

Kuhn (1962/1970) did not clearly express in which discipline a scientific revolution takes place. However, to understand the development of Newtonian mechanics, it is very important to recognize that a revolutionary change in astronomy prepared the change in mechanics, as we saw it in Section 5.2. Sometimes, a radical change takes place in a small field and this change influences the scientific development of a larger field. The example of interactions between the astronomy and the mechanics discussed in Section 5.2 and the example of interactions between the mechanics and the electromagnetism in this section show that some developments in sciences are closely related to each other. In the last part of this paper, we have suggested that ETST is a framework that can properly describe these interactions.

The importance of external coherence for the theory choice indicates an extra problem. The theory choice might depend on accepted relevant theory structures at the given time. On the other hand, an acceptance of a scientific theory structure might change attitudes to other scientific disciplines and other traditional thoughts. Indeed, this kind of change on a large scale took place in the period of scientific revolution in modern Europe.

6 Concluding remarks

In this paper, we proposed *Evolutionary Theory for Science and Technology* (ETST). We have sketched how to apply ETST to an explanation of developments in scientific activities. A theory structure is more precisely characterized than a paradigm and it is more flexible than a scientific research program. Research teams try to extend the accepted theory structures so that they can solve more problems. They sometimes select a better one among some proposed theory structures. In this selection process, they may use three epistemic values, namely accuracy, expressibility, and coherence. These activities of researchers determine the scientific development. We also suggested how scientific and technological activities co-evolve.

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Author Information

Yasuo NAKAYAMA (Osaka University, Graduate School of Human Sciences)