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Coherence Between Theories

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I Introduction

This paper explores the conceptual dimension in theory acceptance, throws light on the notion of coherence between theories, and emphasizes the role of coherence between theories in theory acceptance. It is important, however, to recognize that the empirical-conceptual distinction, like most other distinctions in philosophy, is only pragmatic because purely empirical or conceptual notions in science are rare. That is, the term 'conceptual' is actually used in the sense of 'mostly conceptual', and the term 'empirical' signifies what is predominantly empirical. Yet it is useful in many contexts to speak of conceptual and empirical merits of theories separately. Among the commonly discussed conceptual merits of a theory are internal consistency, simplicity, comprehensiveness, and coherence with existing theories. Empirical merits include accommodating known evidence and passing experimental tests. The focus of this paper is coherence between theories.

II Conceptual Factors and Theory Acceptance

While it is generally agreed that conceptual factors are involved in theory acceptance the extent to which these factors influence acceptance remains debatable. To roughly assess the importance of conceptual elements for acceptance let us address this question: could a theory be accepted before being confirmed? A negative answer to that question entails that acceptance is determined mainly by confirmation, and that the role of nonempirical factors is minimal or secondary. A positive answer, on the other hand, indicates that conceptual factors play a central role in acceptance. By 'acceptance' I mean the judgment made by scientists that a theory is true, approximately true, or very likely to be true and deserves to be added to established theories and used for scientific purposes. The following historical examples may help clarifying to what degree conceptual elements influence theory acceptance.

Slater's theory of oxidative phosphorylation (cellular energy), which was enthusiastically accepted in 1953, postulated that a high-energy intermediate compound transfers energy from the oxidation of fuel substances (e.g., sugars and fatty acids) to the reaction that leads to forming ATP molecules in mitochondria. The latter molecules become the direct source of energy for cellular reactions. This theory was unchallenged for almost two decades, and was used to account for many phenomena at the cellular level, despite the lack of empirical evidence for the existence of its postulated intermediate molecule. In fact, no such evidence was ever found and the theory was discarded twenty years later for that reason.[1] Slater's theory seemed compelling when it was first proposed because it provided a mechanism for ATP synthesis that agrees with available theories in the field without conflicting with known experimental information. In fact, other scientists continued to refine some of the details of Slater's theory until the early 1970's, and this shows that this theory was highly esteemed.

Another example is the theory of DNA structure, which was proposed by Watson and Crick in the early 1950's. This theory, which remains extremely popular in cell biology, entails that the replication of DNA is semiconservative. It was readily accepted and applied to problems in molecular and cellular biology before confirming its main prediction, namely, the semiconservative nature of DNA replication. In fact, this prediction was not unequivocally confirmed until five years later, when the results of Stahl and Meselson's experiments were published.[2]

It is true that the construction of the above theories was based on data from trusted experiments. But this does not imply that they were satisfactorily and adequately confirmed. Indeed, a theory can be based on empirical data but fails confirmatory tests. Examples are numerous and include the theory of Bohr, Kramer, and Slater, which was based on Compton's experimental data but failed to gain confirmation. So a theory may be accepted and trusted by scientists for many years, at least on tentative grounds, without adequate empirical support. This acceptance

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[1] G. Ling, *In Search of the Physical Basis of Life.* (New York: Plenum Press, 1984), 507-509.

[2] S. Wolfe, *An Introduction to Cellular and Molecular Biology*. (Belmont, California: Wadsworth Publishing, 1995), 659-660.

can only be based on conceptual considerations. Among these considerations is coherence between theories.

Gale and Kosso regard the capability of a theory to cohere with established theories as a primary rather than a complementary virtue that heavily influences acceptance. Thus they differ from the vast majority of empiricists, who assign to experimental or empirical support a uniquely prominent status. Gale argues that the coherence of a new theory with established theories within the same discipline is necessary for its acceptance.[3] He provides an account of how theories are accepted at a conceptual level and supports this account by historical examples. According to Gale's view, which he calls 'the conceptualist view', theories are accepted only if they cohere with the conceptions of the prevailing paradigm (i.e., relevant established theories), and their acceptance grows further as their coherence extends to additional areas.

Gale's account, however, tends to underestimate the role of confirmation in the long-term acceptance of theories. He does not address the fact that most theories are tested before they are finally accepted, even if they cohered with relevant background theories. Although many theories were initially accepted (sometimes for decades) before being confirmed, they have been eventually tested. Also, theories whose confirmatory tests were indecisive or equivocal were re-tested at later stages, after being accepted for relatively long periods. So the initial acceptance, which is largely based on coherence and other conceptual merits, is susceptible to revision in light of empirical testing. Consequently, it is more reasonable to propose that coherence between theories plays a role in theory acceptance that is roughly as important as the role of empirical support.

Kosso asserts that the coherence of a new theory with established theories is an important determinant of its acceptance.[4] Yet, unlike Gale, he ascribes proper significance to confirmation by independent evidence and asserts that an acceptable theory is a theory that agrees with both observational evidence and established theories.[5] So Kosso's view does not imply that coherence overrides confirmation as a requisite for acceptance. Yet there is an important agreement between the general ways Kosso and Gale conceive of coherence. It is implicit in their accounts that what coherence between theories amounts to is a significant agreement

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[3] G. Gale, *Theory of Science: An Introduction to the History, Logic, and Philosophy of Science*. (New York: McGraw-Hill, 1979), 220- 226.

[4] P. Kosso, *Reading the Book of Nature: An Introduction to the Philosophy of Science.* (Cambridge: Cambridge University Press, 1992), 38.

[5] Kosso, *Reading the Book of Nature*, 148.

between the cohering theories that enables them to enhance the inferences and consequences of each other.

III Intertheoretic Coherence

Although a number of epistemologists have studied coherence between beliefs or propositions there is no agreement on how propositional coherence should be defined. This lack of consensus on what constitutes coherence is what renders this notion problematic in the field of epistemology. Yet most accounts, whether qualitative or probabilistic, entail that the relation of coherence enables cohering beliefs to 'hang together' or reinforce each other.[6] Eliasmith and Thagard define coherence largely on the same lines. They consider propositions coherent with each other if they 'fit together', and maintain that fitting together is precluded by inconsistency, incompatibility, and negative association.[7] They assert that two propositions (or concepts or other similar elements) cohere if they can be accepted together or rejected together. In that case, there is a 'positive constraint' between them. If a proposition is accepted while the other is rejected, both propositions cannot be considered coherent with each other. There is a 'negative constraint' between them.

Although Shogenji deals with coherence from a probabilistic perspective that employs a formula to measure the coherence degree, he shares the above intuitions about coherence. For example, he agrees that the notion of coherence entails that coherent beliefs hang together. He also maintains that coherence comes in degrees, and this explains why a set containing more coherent beliefs is more likely to be true or to have more true beliefs than a set with less coherent beliefs.[8] Fitelson also proposes a probabilistic account of coherence that shares many of Shogenji's presuppositions but differs in the method of measuring the degree of coherence.[9] The assertion that coherent beliefs are accepted or rejected together implies that coherent beliefs offer each other epistemic reinforcement. Also, the view that an increase in the number of coherent beliefs maximizes the likelihood of their truth supports the conception

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[6] See, e.g., L. BonJour, *The Structure of Empirical Knowledge.* (Cambridge: Harvard University Press, 1985), 91.

[7] C. Eliasmith and P. Thagard, 'Waves, Particles, and Explanatory Coherence,' *The British Journal for the Philosophy of Science,* 48 (1997): 7- 9.

[8] T. Shogenji, 'Is Coherence Truth Conducive?' *Analysis* 59 (1999): 338-45.

[9] B. Fitelson, 'A probabilistic Theory of Coherence,' *Analysis* 63 (2003): 195- 99.

that coherent beliefs increase the epistemic worth of each other, and this is a form of mutual reinforcement.

Gale and Kosso regard the mutual reinforcement between theories the basis of their coherence with each other. So intertheoretic coherence borrows from propositional coherence the notion of mutual reinforcement or support, as manifested by the ability of cohering theories to be accepted and retained together. The fact that the concept of propositional coherence still needs clarification should not preclude utilizing its basic constituent (i.e., mutual support) to characterize intertheoretic coherence.

Intertheoretic coherence does not inherit the problems that afflict propositional coherence because the former kind of coherence is not, in a strict sense, a direct consequence of the latter. That is, intertheoretic coherence is not readily and simply reducible to propositional coherence. The reason is that theories are not ultimately reducible to discrete propositions. Theories are complex structures that include, in addition to assertions and beliefs, mathematical constructs, equations, and analogical models that do not translate into simple, circumscribed beliefs. But intertheoretic coherence is a relation that is understood by analogy with, and after the example of propositional coherence. Consequently, issues that are specifically related to propositional coherence will not be discussed in this paper.

1. Theories are Arranged in Clusters

In scientific practice, theories that deal with the same class of issues in similar ways are usually combined together in a cluster. For example, there is a cluster of theories dealing with thermodynamics, another with electromagnetism, a third with molecular biology, and so forth. This strongly suggests that theories are not grouped together randomly but according to specific criteria. To identify such criteria one needs only to examine the relations between various theories within a cluster.

Although it may appear from the first look that theories are arranged in clusters according to the topics they address a closer look at actual clusters of theories shows that members of a cluster do not merely deal with similar topics. For example, theories of enzymatic catalysis and theories of heavy-metal catalysis (which address chemical catalysis) are not grouped together, and a student of biochemistry would not encounter a discussion of metal catalysts in a textbook or a journal of biochemistry. The reason seems to be that most of the concepts of enzymatic catalysis do not apply to heavy metal catalysis and vice versa. Similarly, Newtonian mechanics is not currently included with relativistic mechanics in the same cluster although both systems deal with closely related topics. If they were combined together in one system, such a system would be heterogeneous and inconsistent.

The relation between Newtonian and relativistic mechanics needs further clarification. Early in the twentieth century, many physicists suggested that Newtonian mechanics can be dealt with as a limiting case of relativity because it can be applied to small-scale phenomena and reach results that are very close to those obtained by relativistic mechanics. Would not that indicate that both theories are consistent with each other and belong to the same cluster? To answer this question let us briefly characterize limiting case relations. These relations are based on the notion that omitting one or more parameters from a new theory can lead to minimizing its incompatibility with its predecessor. This view is derived from Bohr's correspondence principle, which entails that theories of quantum physics reduce to classical mechanics when Planck's constant is neglected.[10]

As Krajewsky has clearly shown, limiting case relations can be established only by eliminating the parameters in the new theory that conflict with the laws and values included in the old theory.[11] So Newtonian mechanics becomes a limiting case of relativistic mechanics only when some values in the relativistic equations are made equal to zero. But relativistic mechanics prohibits the possibility that the velocity of light can be infinite. This indicates that Newtonian mechanics is not compatible with relativistic mechanics. So limiting case relations do not imply that two theories are consistent with each other. Such theories become consistent with each other only when the equations of one of them are altered and some parameters are disregarded. Such consistency is artificial and is attained by means of reformulating a theory in a modified form for pragmatic rather than epistemic reasons. Indeed, limiting case relations merely represent counterfactual situations and may be useful only for practical applications when simplified calculations are required. These relations do not imply the deducibility of one theory from another.

Coherence between theories is first suspected when these theories are consistent with each other and agree on some basic elements or assert similar assumptions, concepts, equations, or models. Further examination may show that these theories not only make similar assertions but also enhance the productivity of each other. For example, a theory about cellular respiration in mitochondria may lend support to a theory about the cytoplasmic metabolism of a class of substrates by demonstrating

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[10] M. Jammer, *The Conceptual Development of Quantum Mechanics.* (New York: McGraw-Hill, 1966), 80-81.

[11] W. Krajewsky, *Correspondence Principle and Growth of Science* (Dordrecht: D. Reidel, 1977), 6-7.

that the products of cell respiration stimulate some metabolic steps in the cytoplasm. By showing that, the former theory supports the basic assertion of the latter. At the same time, the latter theory may explain the mechanism of transport of certain molecules from the cytoplasm into mitochondria, where they participate in reactions of cell respiration. This would clarify a mechanism that the former theory proposes. In a scenario like that, both hypothetical theories reinforce each other, in addition to being mutually compatible. Such hypothetical theories are tightly related. They can be described as coherent with each other.

At the same time, theories that do not address related issues or those that adopt extensively divergent approaches to the same issues are not included in the same cluster. Such theories can be described as incompatible, hence noncoherent. Compatible theories are logically consistent and address related issues by means of similar strategies. Similarly, theories that lack significant inferential links are not grouped together. For example, Einstein's theory of the photoelectric effect, the kinetic molecular theory of gases, and the transition state- theory of enzymatic catalysis are not placed together in the same cluster. Although these theories have no conflicting concepts or consequences it seems unlikely that they can have significant inferential connections. If they were gathered in one cluster, it would be of limited usefulness because it would provide no advantage for scientists over using its constituent theories separately. Moreover, the usefulness of such a divergent cluster will not increase or decrease by removing from it one or more theories.

So the arrangement of scientific theories in clusters is not arbitrary and is not based on superficial similarities. Rather, it is based on qualities that ensure that theories in a cluster can be efficiently used together to multiply scientific inferences and expand scientific information. These qualities are compatibility and the existence of close inferential links between theories. It follows that members of a cluster of theories are both compatible and inferentially related. This explains why scientists face no difficulty while using these theories together by utilizing elements from each of them to formulate new hypotheses, explanations, or other consequences.

Typically, scientists use several theories in a cluster rather than an individual theory for solving problems. For instance, when scientists address a problem in electromagnetism they usually draw inferences and utilize concepts from several electromagnetic theories or hypotheses at the same time. For example, Hertz utilized in his work concepts from the theories of Ampere, Faraday, and Maxwell.[12] In a similar manner, a

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[12] See, e.g., J. Taylor, *Hidden Unity in Nature's Laws*. (New York: Cambridge University Press, 2001), 91-97.

scientist studying a protein that induces cancer in cells would utilize concepts from theories of cell cycle, embryonic development, molecular chemistry, and so on. The reason why scientists often utilize large segments of a cluster seems to be the capability of broader systems of theories to produce significant information. However, a scientist addressing a narrow and confined problem may need to use a single theory.

A plausible explanation for the fact that large clusters produce more information than do individual theories is that theories in a cluster supplement each other, thus maximizing the information that can be drawn from their cluster. For example, the cluster of early quantum theories contained theories that explained the discrete nature of heat and light, and the discontinuous emission of radiation. Without these explanations, for example, Bohr would not have been able to postulate the existence of stationary states in atoms (where electrons do not emit energy all the time but periodically), and his atomic model would have not overcome the difficulties that crippled Rutherford's atomic model.

Based on the above discussion, it can be asserted that clusters of theories contain members that allow generating from their components effective inferences and consequences, which were not originally obtainable from the individual members. The ease with which scientists construct new information (e.g., explanations, predictions, or models) from several theories within a cluster reflects the tightness of the inferential relations that exist between them. Thus coherent clusters produce significant scientific data. This leads to scientific progress and, probably, correct scientific assertions. So the fact that some theories cohere together implies that they can be more productive when combined in the same set of theories.

2. *Defining Intertheoretic Coherence*

It would be useful at this point to clarify how theories relate to each other in a positive manner. A positive relation ties together various theories rather than disconnects them from each other. There is a hierarchy of positive relations between theories. Two theories would be consistent with each other if none of them contains elements that negate or conflict with some elements in the other. If these theories, in addition to being consistent, share some elements (e.g., concepts, mechanisms, or equations), follow similar strategies of reasoning, or agree on some basic notions, they go beyond mere logical consistency and can be said to be compatible with each other, as already pointed out. Compatibility, then, can be construed as the absence of conflicts and the presence of some agreements (theoretical, empirical, or methodological), however limited. As can be readily expected, consistency is a loose relation. For example, Quantum mechanics is consistent with any theory within the realm of molecular biology. Compatibility, on the other hand, is a more tight relation. For instance, quantum mechanics is compatible with theories of atomic structure. Coherence is even tighter. As an example, the wave theories of light of the nineteenth century cohere with each other. They share common notions (e.g., propagation of light in waves caused by oscillations in the ether and the mechanisms of refraction and diffraction) and contain no concepts that clash with each other. They also have inferential connections, as can be realized from the equations that link their parameters to each other.

Compatibility is sometimes achieved gradually. When a theory that is compatible with some members of a cluster is accepted some of the concepts and assumptions within the cluster may need further adjustments to eliminate any conflicts resulting from adding new theoretical notions. The appearance of novel concepts often requires reinterpreting some of the older concepts to expand the conceptual consistency within a cluster. Compatibility, then, is seldom a steady state or a static condition.

Thus far, it has been argued that clusters contain inferentially connected theories, and that this feature, which can be referred to as complementarity, facilitates drawing new, synthetic information from several compatible theories. So the features that characterize coherent clusters are compatibility and complementarity. These features, at the same time, define intertheoretic coherence. In other words, intertheoretic coherence consists in compatibility and complementarity between theories. Thus the definition of intertheoretic coherence is derived, in effect, from the way scientists arrange theories in clusters. It can also be asserted that two coherent theories act in concert, owing to their mutual inferential connections, to produce useful information that is not derivable from any of them individually.

If compatibility and complementarity were not required for cluster membership, theories addressing the same issues from radically different perspectives (e.g., Newtonian and relativistic mechanics) would have been grouped together. Also, there would have been clusters in science that explore unrelated topics or produce inconsistent consequences. Moreover, if a cluster contained incompatible or inferentially disconnected theories, its utility would not be affected by removing some of its members or adding more divergent members. This is because, as indicated earlier, no important inferential links exist between irrelevant theories. Reducing or increasing the number of the members of such a cluster, which lacks coherence, would not change its fruitlessness for scientific purposes. In contrast, coherent clusters would be seriously affected by losing some of its members. For instance, the set of theories of thermodynamics would lose a significant part of its effectiveness if

Gibbs's theory of free energy was excluded from its membership. Discarding this theory would prohibit many useful inferences and eliminate several concepts, such as the spontaneity of a process.

Furthermore, the synthetic and unifying concepts and explanations that are generated by combining notions from this theory and other theories in the cluster would not have emerged. For example, the concept of equilibrium constant would not be possible to formulate if either Gibbs's theory or Boltzmann's theory of entropy were removed from thermodynamics. According to thermodynamics, equilibrium constant is a value that determines whether a reaction has reached equilibrium, i.e., its net energy has not changed because the free energy of the forward reaction is precisely balanced by the backward reaction. Similarly, removing theories of molecular genetics from molecular biology would undermine the productivity of molecular biology.

Complementarity is frequently reflected in the ability of theories to clarify the concepts, increase the applications, and enhance the explanations of each other. More generally, complementarity between theories is reflected in the capability of the cluster that includes them to promote scientific reasoning by providing the required inferences for generating more information. As a consequence, the effectiveness of a cluster depends to a large extent on the degree of complementarity between its theories. A good test for the presence of complementarity would be the decrease in the fruitfulness of a cluster as a result of removing some of its theories or the increase in its utility by adding new inferentially connected theories to its existing members. This is because the loss of a theory from a homogeneous cluster implies the loss of a number of inferential connections among its members and the gain of a theory implies a gain of more inferential links between its members.

IV How Theories Become Coherent with Each Other

Let us briefly review what renders two theories coherent with each other. Theories acquire coherence if they are compatible and at least one of the following conditions is available. First, coherent theories share common elements and address similar or identical topics and also possess inferential connections with each other that enable scientists to explore issues that were difficult to investigate by one of them. Second, they can explain phenomena that one of them alone may not explain effectively. Third, when used together they may produce predictions that one of them alone cannot produce. Fourth, both theories, when used together, can contribute important elements to other theories that cannot be obtained from either theory alone. Fifth, when coherent theories are used together they may be able to cover domains that were not open to any of them individually.

It should be emphasized, however, that although coherence between theories is predominantly a conceptual virtue, cohering theories tend to acquire empirical support from one another. For example, Bohr's atomic theory, which cohered with Plank's quantum theory, benefited form the empirical support that Plank's theory enjoyed. So the empirical support of a theory adds some degree of empirical strength to the newly introduced theory that coheres with it. Such empirical strength can enhance the acceptance of the new theory. Yet it would be farfetched to regard a theory confirmed on the sole basis of its coherence with a confirmed theory.

V Clusters Differ from Paradigms

The reader may perceive some degree of resemblance between Kuhn's concept of paradigm and theoretic clusters. If there was any resemblance, it would be very superficial and trivial. Scientists are not uncritically committed to any cluster, and their intellectual commitments to clusters are not as rigid as the commitment described by Kuhn to a paradigm. For them, a cluster, unlike a paradigm, is internally modifiable and alterable. They do not have to either accept a cluster in its original form or desert it totally. They conceive of a cluster as a group of theories rather than a comprehensive way of looking at reality. Scientists can, and do work with more than one cluster at the same time, depending on the studied subject, which does not happen in the case of paradigms. Clusters are considered testable and revisable, and are treated as tools of producing inferences and maximizing information. Kuhnian paradigms are not conceived the same way, and scientists, supposedly, do feel strongly about them. Moreover, the view that theories are arranged in clusters does not entail that scientific revolutions are necessary developments that follow the emergence of problems within a cluster.

VI Other Characteristics of Intertheoretic Coherence

1. A coherent Cluster is not a Single Large Theory

Intertheoretic coherence does not have to be extensive. It is not demanded in science that every component of a theory within a cluster affirm every component in other theories in the same cluster. In fact, the history of science shows that a new theory needs only to share some basic aspects (e.g., some core assumptions or major consequences) with established theories in a cluster in order to be added to that cluster, provided that it does not negate or disagree with any of the other aspects. For example, Stark's theory of discrete spectral lines affirmed the conception of stationary states in Bohr's theory of atomic structure.[13] The coherence between both theories is evident from the mutual reinforcement (complementarity) they provide for each other in the field of spectroscopy. But Stark's theory neither affirmed nor conflicted with the mechanical aspects of Bohr's atomic model, such as the notion of electron momentum.

Indeed, as the history of science suggests, every theory contains elements that are not addressed by the other members of the cluster. These elements may or may not have direct inferential relations with all the elements in the other theories of the cluster but they should not conflict with any of the basic components of these theories. However, every theory in a cluster shares at least a few basic components with other members or has elements which are closely linked with elements of other theories by direct inferential ties. It should be clear, then, that cohering theories in a cluster do not constitute sub-theories within a comprehensive, extended theory.

2. The Gradual Growth of Intertheoretic Coherence

Achieving intertheoretic coherence in a cluster is a dynamic and continuing process. With scientific change, new clusters emerge and coherence between their theories grows gradually. With further refinement and broadening of the theoretical elements of a cluster the coherence between its members increases. Scientists are sensitive to theoretical conflicts and try diligently to eliminate them, and this attitude tends to preserve and maximize coherence. But scientific change may also produce minimal inconsistencies, i.e., not involving the main assumptions and do not require altering the basic notions of existing theories. These, as a general rule, are transient. They often result from adding new theories with novel concepts whose inferential relations with older notions may need time to be established. Such inconsistencies are commonly corrected shortly after accepting new theories.

However, the extent of intertheoretic coherence in a cluster is seldom constant. Adding, removing, and modifying theories within clusters never cease in science, and this leads to fluctuations in the degree of the internal coherence of a cluster. When coherence diminishes to an extent

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[13] J. Mehra and H. Rechenberg, *The Historical Development of Quantum Theory* (2 volumes), (New York: Springer-Verlag, 1982), 189.

that scientists do not accept, scientific change (or extensive revisions) may follow and a rival cluster or part of it may replace the older one.

3. Theory Change Within a Cluster

As already pointed out, every theory in a coherent cluster is, in a sense, unique because each theory introduces elements that have not been previously addressed. Thus every individual theory retains a degree of independence, which allows it to be assessed and scrutinized separately. This opens the door for the rejection or replacement of an individual theory within a cluster. So when a new, more effective theory is proposed and seems to cohere with the relevant cluster it may replace an older, less advantageous theory. The decrease of coherence in a cluster that may follow discarding a theory is frequently repaired by replacing it with another theory that coheres with the rest of the cluster. Another repair mechanism is modifying the concepts or assumptions of the retained theories in the cluster. Indeed, this gradual process of refining clusters is constantly operating in science and is commonly referred to as the gradual type of theory change. This process should not alter intertheoretic coherence as long as newly introduced theories cohere with existing theories and modifications in established theories do not produce conflicting elements.

4. Revolutionary Change and Coherence

However, discarding the major or central members of a cluster is likely to weaken the coherence between other members and may subsequently result in rejecting the whole cluster. A major theory is a theory that addresses the fundamental topics in the field or acts as a basic source for the elements of other theories in the cluster. The rejection of major theories or a core theory in a cluster can be a sign of accelerated or revolutionary change. Among the best examples for this phenomenon is the replacement of classical mechanics with the early system of quantum physics.

While the gradual form of theory change seems to pose no threat to the view that clusters are internally coherent and that intertheoretic coherence is important for theory acceptance, accelerated change may appear challenging to this view. The potential challenge stems from the following question. It is agreed that accelerated change implies that a new, coherent cluster replaces an existing coherent cluster within a short period of time. How could this be reconciled with the assertions, advocated in this paper, that theory acceptance is a gradual process and that intertheoretic coherence is achieved gradually?

This challenge, however, becomes unsustainable if the history of science shows that accelerated theory change does not involve accepting a whole coherent system of theories in a single step then rejecting an established system which does not cohere with it. In other words, the coherentist view is not threatened if accelerated theory change advances quickly in discrete steps. Let us reflect on the transition from classical mechanics to quantum physics, which Segre describes as 'one of the greatest revolutions in natural philosophy'.[14] The following account briefly outlines its main developments.

The first quantum theory was Planck's theory of blackbody radiation, which appeared in 1900. It is well known that most aspects of Planck's quantum theory cohered with classical mechanics. Only Planck's conception of discontinuous emission of radiation was subsequently (but not initially) found by a number of physicists, not including Planck, to conflict with classical mechanics. So Planck's theory does not represent a counterexample to the coherentist view because it was considered coherent with the established classical theories for eleven years after its acceptance. Yet there was no immediate solution for the apparent inconsistency between its notion of discontinuous radiation and Maxwell's theory, and this led to an extended debate. It was not until 1911 at the First Solvay Conference that physicists agreed that Planck's theory does not cohere with Maxwell's theory, but Planck continued his attempt to modify his theory to render it coherent with classical mechanics.

Meanwhile, quantum theories that failed to cohere with classical mechanics, such as Einstein's theory of light quanta and Stark's theory of atomic constitution of radiation (published in 1909), were rejected. In contrast, Bohr's theory of atomic structure was accepted because of its coherence with classical mechanics. Other quantum theories remained in the class of explored (or pursued) theories pending the resolution of the debate over the coherence between Planck and Maxwell's theories. When, finally, classical mechanics was abandoned in 1923 physicists reaffirmed their commitment to the construal of Planck's notion of quantum of action which conflicted with classical mechanics. They disapproved of Planck's attempt to modify this notion to bridge the gap between quantum physics and classical mechanics.[15] Thus Planck's quantum theory was transferred from classical mechanics to quantum

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[14] E. Segre, *From X-Rays to Quarks: Modern Physicists and their Discoveries.* (San Francisco: W. H. Freeman and Company, 1980), 76.

[15] J. Hendry, *The Creation of Quantum Mechanics and the Bohr-Pauli Dialogue* (Dordrecht: D. Reidel Publishing Company, 1984), 31-41.

physics. Once that happened, the quantum theories that cohered with Planck's theory but not with classical mechanics were transferred from the sphere of pursued to that of accepted theories.

So the 'quantum revolution' took place in the following steps. First, discovering incoherence between two major members of classical mechanics, namely, Planck and Maxwell's theories. Second, discovering that combining Planck's theory with the explored new quantum theories produces a more effective cluster than that of Planck's theory and classical mechanics. Third, adding to the new cluster the few theories that cohered with both classical mechanics and newer quantum theories, such as Bohr's atomic theory. Fourth, rejecting classical mechanics and accepting quantum physics on the basis of new experimental evidence that favored quantum physics. This shows that the ultimate rejection of classical mechanics had to wait until the explanatory superiority of explored theories of quantum physics became obvious and the empirical support for quantum theories became undeniable. This brief review of the evolution of quantum physics between 1900 and 1923 strongly suggests that accelerated scientific change advances in fast steps rather than abruptly. That is, this form of scientific change differs from the more common and gradual change in the duration of its steps rather than in the general scheme of theory change.

Thus revolutionary changes can be easily accommodated by the view proposed in this paper. Although the above outlined view of accelerated gradual change disagrees with the Kuhnian view of abrupt scientific change it is important to notice that it is not intended as a detailed discussion of the issue of scientific revolutions. Such a discussion would unnecessarily shift the focus of this paper.

5. Clusters of Theories are Relatively Independent

Generally, there are no significant inferential connections between most separate clusters. For example, both clusters of thermodynamics and cell biology are internally coherent but they cannot be said to cohere with each other. It is true that they share a number of laws, concepts, and empirical data. But they do not share enough elements to allow generating unifying inferences or combined concepts from them. This implies that coherence is not pervasive enough in science to allow for constructing giant unifying theories that explain a multitude of phenomena. Coherence is mainly observed between theories within clusters but not between theories from different clusters. This does not indicate that coherence in science is of limited significance. Rather, it indicates that some areas of scientific investigation can be better approached by different systems of theories. For example, problems related to gravitation and the passage of light in empty space at a cosmic scale are more amenable to relativistic than to quantum mechanical approaches. For this reason, they are dealt with through clusters of relativistic theories.

The fact that various clusters of science do not cohere with each other implies that the ideal of achieving unity in science has not yet been accomplished. It is true that some concepts in different clusters can be reduced to the basic concepts of other clusters. For instance, many biological notions are reducible to chemical and physical concepts. However, such reductionism is still incomplete. Further advances in the direction of scientific unification seem to require achieving more coherence between clusters of theories, both within the same discipline and among different disciplines. For example, there are several clusters within physics (such as relativistic and atomic physics) that are separated by inferential gaps and remain insufficiently coherent with each other. But it is beyond the scope of this paper to speculate about the feasibility of such unification.

There are, however, some instances in the history of science where notions and assumptions from theories that belong to different clusters are used together to devise new theories. For example, some theories of quantum mechanics that were proposed between 1925 and 1945 contained notions from quantum theories (e.g., quantum view of the atom) and classical theories (e.g., classical description of the electromagnetic field). The result was a new cluster of quantum theories, which were called 'semi-classical theories'. Similarly, concepts from quantum theories of matter and general theory of relativity were combined to form a group of theories, which are also considered semi-classical theories. More recently, theories of molecular biology used notions from physics, inorganic and organic chemistry, and biochemistry. In these instances, notions from incompatible theories are utilized to construct new theories. Would such a phenomenon challenge the view that compatibility is required for cluster membership? The answer is negative.

Clusters that utilized notions from incompatible theories and formulated hybrid concepts remained internally coherent. That is, the clusters of semi-classical quantum theories, relativistic quantum mechanics, and molecular biology theories contained only theories that are compatible with each other. What matters for intertheoretic coherence is whether a cluster contains compatible theories, not whether these theories were constructed from homogeneous concepts and assumptions. That is, consistency is not always required for building theories but it is required for forming clusters of theories.

VII The Role of Coherence: Historical Examples

The following examples may shed light on the importance of conceptual considerations, particularly intertheoretic coherence, in the early stages of theory acceptance. Although the term 'model' is frequently used in science to designate a component of a theory that describes a structure or a mechanism there are theories that consist mainly of detailed descriptions of structures or mechanisms. Rutherford and Bohr's models of atomic structures are good examples for such theories. Both models possess the basic attributes of a theory. They describe an aspect of the world, provide explanations for important phenomena, lead to empirical predictions, and contain inferences, formulas, and other common theoretical elements. They also have testable consequences. So it is warranted to deal with these models as theories.

An illustrative example for the importance of coherence for theory acceptance is the rejection of Rutherford's model of atomic structure, which was empirically supported. Rutherford's model does not merely consist of a description of the structure of the atom. Although it is mainly concerned with depicting the composition of the atom it also aims to justify the stability of the atom by proposing that electric attraction keeps negatively charged electrons rotating around the positively charged nucleus permanently. Moreover, the outer layer of the atom, which consists of rotating electrons, protects the nucleus from external, disruptive forces.[16] So this model had explanatory strength and was built upon significant experimental observations. Later, however, its attempt to justify the stability of the atom was questioned.

Rutherford's model or theory was supported by the elegant experiments in which alpha particles emitted with high velocity were used to collide with material surfaces and the deflected particles were traced by photographic plates. Most particles were not deviated by the collisions and only a few were scattered due to the purported collision with thin material layers. The theory was able to spell out the structure of the atom by analogy with the solar system. According to Rutherford, alpha particles were scattered because they were repelled by the positively charged nuclei in the atoms within the metal sheets, and this points to the existence of a central bulky nucleus in the atom, surrounded by huge empty space in which electrons rotate in their orbits.[17]

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[16] G. Amaldi, *The Nature of Matter: Physical Theory from Thales to Fermi*. Translated by P. Astbury, (Chicago: University of Chicago Press, 1982), 61.

[17] E. Rutherford, 'The Scattering of alpha and beta Particles by Matter and the

Nonetheless, Rutherford's theory was rejected because of its failure to square with Maxwell's theory.[18] Maxwell's equations entail that orbiting electrons should emit electromagnetic energy during rotation in their orbits, a process that is bound to cause the electron to lose most of its energy and eventually collapse on the nucleus. Rutherford's theory was rejected as soon as this conflict with Maxwell's theory, and, consequently, with many other theories of classical mechanics, was recognized. It was replaced by Bohr's theory, which avoided such a conflict.

Einstein's theory of light quanta was proposed and instantaneously rejected in 1905. Einstein's theory (or hypothesis) proposed that light propagates as independent energy quanta rather than a continuum of waves. Eighteen years later, the same theory was accepted although it was not modified during these years. This theory met with strong opposition for many years because it conflicted with Maxwell's theory of electromagnetism and lacked empirical evidence. Yet the eminent physicists who rejected this theory (such as Lorentz, Planck, Bohr, and Wien) emphasized that the primary reason behind their rejection was the incompatibility of Einstein's notion of light quanta with theories of classical mechanics, particularly Maxwell's theory.[19] Planck carefully explained in his correspondence with Einstein that his objection to the concept of light quanta stemmed from its disagreement with Maxwell's equations.[20] According to these equations, which appeared compelling to almost every physicist in the late nineteenth and early twentieth centuries, light should behave like waves as soon as it is emitted by matter. But Einstein's theory depicts light as discrete 'packets' of energy that behave in a particulate manner, reminiscent of Newton's pulsating particles of light. Newton's theory, of course, was already discarded while Maxwell's theory was valued for its ability to accommodate the experimentally supported wave theory of light and to unify it with electricity and magnetism.

The classical theories of electromagnetism comprised the background, established theories for Einstein's theory of light quanta until the classi-

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Structure of the Atom', in Boorse, H. And Motz, L. (eds.), *The World of the Atom* (New York, London: Basic Books, 1966), 701- 731.

[18] Amaldi, *The Nature of Matter*, 60- 64.

[19] See M. Jammer, (1966), 43- 53, and W. Heisenberg, *Encounters with Einstein and Other Essays on People, Places, and Particles.* (Princeton: Princeton University Press 1983), 21.

[20] See, e.g., his letter of 1907, quoted in Hermann, A. *The Genesis of Quantum Theory (1899-1913).* Translated by C. Nash, (Cambridge, MA: The MIT Press,1970), 56.

cal theory of electrodynamics was replaced by the early quantum theories. The appearance of supporting evidence for Einstein's theory in 1916, which derived from Millikan's experiments, did not improve its situation. It is true that Millikan's Experiments were not originally intended to test this theory but they provided empirical data that were sufficient for confirming it. As the physicists of that time saw it, the problem with the notion of particle-like photons was more conceptual than empirical. They were unable to tolerate the discrepancy between light quanta and classical physics and this is why they were not impressed by Millikan's evidence when it was published in 1916.

It is well known that the theory of light quanta threatened the acceptance of Einstein as a member in the Prussian Academy of Science in 1913 because of its unpopularity among physicists.[21] But after Compton's experiments consolidated the corpuscular concept of radiation around 1922, Maxwell's theory of classical electrodynamics was abandoned.[22] As a result, the new cluster of background theories for Einstein's theory included no theory that conflicted with the conception of discrete light quanta. Indeed, the relevant background theories for Einstein's theory by 1923 became the early quantum theories of Planck, Bohr, Stark, and Nicholson, which received support from Millikan's experiments on the nature of electricity and from Compton's experiments on X-ray scattering. Upon realizing that these new theories cohered with the theory of light quanta, the latter was revisited and accepted.[23]

It could be argued that the failure of Einstein's theory to accommodate the two-slit experiment on the nature of light was the crucial factor in its rejection. Yet the same theory was subsequently accepted despite its failure to accommodate that experiment. Meanwhile, it would be implausible to point to Compton's experiments as the decisive element in the acceptance of Einstein's theory. These experiments were not more confirmatory of this theory than Millikan's work. In fact, Compton's experiments helped the acceptance of some quantum theories, including Einstein's, by invalidating the basic assumption of classical theories, namely, that radiation proceeds in a continuous manner, rather than by directly confirming the early quantum theories. It would not be exaggerated to say that if these experiments reconfirmed Einstein's theory without challenging Maxwell's theory, the existence of light quanta

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[21] F. Hund, *The History of Quantum Theory.* Translated by G. Reece, (London: Harrap, 1974), 50.

[22] Hendry, *The Creation of Quantum Mechanics*, 36-37.

[23] Jammer, *The Conceptual Development*, 36.

would have remained doubtful until the ultimate demise of classical mechanics.[24]

VIII The Regulatory Aspect of Coherence.

The requirement of intertheoretic coherence for accepting a new theory can be useful for science in different ways. Accepting a theory that conflicts with established theories may eventually lead to rejecting some or most established theories in the relevant field. The reason is that scientists do not accept two theories that address the same issues but remain inconsistent with each other. They will ultimately discard one of them, which may well be the older, established theory. This may end in losing some well-structured and fruitful theories that proved successful for years or decades. If scientists uncritically accept every promising theory that displays good qualities while being explored, science is likely to lose some of its best established theories. So giving proper consideration to intertheoretic coherence can prevent hasty acceptance of attractive or promising theories that have not yet been studied in depth at the expense of some theories whose merits have been well ascertained. Of course, the requirement of empirical support also discourages premature acceptance of new hypotheses and theories. But empirical methods are not always immediately decisive and often need to be refined and improved before they yield compelling results.

This does not mean that the criterion of coherence will always lead to a conservative, rigid attitude to new theories. Rather, it leads to a cautious, critical approach to the acceptance of explored theories. This restraining role of coherence is similar to the role of confirmation, which tends to select the best constructed theories and to prevent uncritical acceptance. Most experienced scientists tend to be cautious, and this is a useful attitude in science. Without such caution, several theories that looked persuasive in the beginning but were eventually found defective would have been accepted. Consider, for example, the theory of Bohr, Kramer, and Slater, which was proposed in 1924 to provide an alternative explanation for Compton's data.[25] This theory, which initiated instantaneous enthusiasm and curiosity as soon as it was published, stated

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[24] For an analysis of this episode see L. Brown, A. Pais, and B. Pippard, *Twentieth Century Physics, Volume I.* (London and New York: Institute of Physics Publishing & American Institute of Physics Press, 1995), 163-166.

[25] Brown, Pais, and Pippard, *Twentieth Century Physics,* 165-166.

that energy is conserved in interactions between atoms and radiation only statistically (on average rather than in every individual interaction). If it were accepted, the principle of energy conservation, which underlies most laws of physics and chemistry, would have been seriously threatened. But this bold theory was conceptually then empirically discredited within a year of its exploration. In fact, this theory was first rejected because of its incoherence with the principle of energy conservation before its conflict with experimental findings was recognized shortly after.

So the criterion of intertheoretic coherence, by encouraging meticulous examination of new theories, is capable of acting as a useful regulatory principle or a methodological constraint. The need for such constraint should not be underestimated, given the fact that new, promising theories are proposed daily in every scientific field, and many of them are found defective when seriously scrutinized.

The criterion of intertheoretic coherence also acts as a constraint on fast (revolutionary) theory change. There are always competing theoretical systems in science. While scientists in a field are usually committed to one theoretical system (cluster or related groups of clusters of theories) they explore competing ones. The failure of an established system to resolve a scientific issue may prematurely motivate scientists to replace it instead of trying more carefully to refine its components. The problem with a decision to replace an accepted cluster with an explored one is that empirical data seldom help favoring any of the competing clusters early enough. Most empirical data contain approximations and equivocal findings and, for this reason, are open to different interpretations. Experiments that can decisively favor a system over its rival take a relatively long time to be developed. Recall that the experiments that prompted the demise of classical mechanics came more than ten years after the beginning of the intense debate over the choice between classical and quantum theories.

Could the cautious attitude that is reinforced by the requirement of coherence impair scientific progress? In theory, it is possible that this requirement leads to resisting scientific change. Yet it is more plausible to suggest that the criterion of coherence adjusts the pace but does not arrest scientific change or inappropriately delays it. This suggestion is supported by the fact that the restrictions imposed by the requirement of coherence for theory acceptance has not precluded scientific change, which continues relentlessly. As already seen, the transition from classical mechanics to quantum physics was slowed but not precluded by the requirement of coherence. This allowed the physicists of that era to make prudent decisions regarding theory rejection and acceptance. So slowing theory replacement allows scientists to examine proposed theories more thoroughly and accept the ones that are likely to be true. It also allows them to reexamine older theories carefully before deciding to discard them, and consequently, to preserve the true ones.

IX Conclusion

Conceptual (or predominantly conceptual) factors, including especially intertheoretic coherence are not less important for theory acceptance than empirical factors. As scientific practice indicates, theories are arranged in clusters such that the members of a cluster cohere with each other. This implies that scientists are careful to add a new theory to the cluster with which it coheres. In other words, scientists act according to a preconceived scheme that favors grouping coherent theories together. It follows that intertheoretic coherence, defined as the presence of compatibility (some agreements and no important conflicts) and complementarity between theories, is an important determinant of theory acceptance in scientific practice. If scientists did not require intertheoretic coherence for acceptance, they would have constructed heterogeneous and inherently inconsistent clusters of theories by accepting divergent theories in the same field. Yet coherence is not generally encountered between clusters of theories. An important feature of intertheoretic coherence is that it acts as a constraint on scientific change by restricting imprudent and uncritical theory replacement.

Finally, it is important to maintain that further work is still required to clarify the exact relation between propositional coherence and intertheoretic coherence in more depth. Also, the regulatory role of coherence in scientific change needs more detailed discussions. Indeed, this paper is intended as an introduction to the issue of coherence between theories.

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