On the Implications and Extensions of Luk's Theory and Model of Scientific Study

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Abstract

Recently, Luk tried to establish a model and a theory of scientific studies. He focused on articulating the theory and the model, but he did not emphasize relating them to some issues in philosophy of science. In addition, they might explain some of the issues in philosophy of science, but such explanation is not articulated in his papers. This paper explores the implications and extensions of Luk's work in philosophy of science or science in general.

Keywords: philosophy of science, methodology, scientific knowledge, realism, theory and model

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1. **Introduction**

Luk (2010; 2016) constructed a theory and a model of scientific studies. His (process) model shows clearly that (pure) science consists of theories, models, experiments and physical situations. Based on these constituents, the stages of science development are identified. His theory states the common principles and assumptions in science for which scientific investigations are carried out. The theory also has a general aim of scientific study or science so that all activities and products of science are supposed to aim at. However, Luk did not emphasize relating the model and theory of scientific studies to some issues in philosophy of science nor explain why science is organized the way it is, because he tried to present the theory and the model first. Here, we explore the implications and extensions of his theory and his model in order to address these issues. We discuss each issue section by section.

Specifically, Section 2 discusses the general issue whether there is general science. If there is no general science, then there is no general aim for general science, which we discussed in Section 3. Given that there is science and it has a general aim, Section 4 examines whether we should limit science based on the object of study. As we argued that we should not limit science to natural science, we have to examine the nature of science more carefully in Sections 5 - 10 as science may include subjects that may not be considered as science before. Section 5 looks at the structure of scientific knowledge where there is some confusion between theory and model in the semantic view of science. Section 6 explains the scientific progress of science which may not follow Kuhn's idea of scientific revolution. Section 7 addresses the nature of scientific knowledge which is often assumed to be (almost) certain (especially in physics). Section 8 addresses the more specific problem on whether scientific models can be logical models (as some subjects now considered as science may only have logical models rather than quantitative models). Section 9 clarifies whether there can be or cannot be any bias in experiments, and the principle behind allowing bias is that the experiment is done fairly intentionally or the bias is introduced unintentionally. Section 10 explores the possibilities that science deals not only with verification or falsification but both, so the philosophical argument about whether science verifies or falsifies is a non-issue. Finally, some general and often debated philosophical issues are addressed in Sections 11 - 14. These include reductionism (Section 11), scientific realism

(Section 12), uniformitarism (Section 13) and what is science (Section 14). Section 15 addresses a recent controversy in science (i.e., is string theory science?) in which philosophy of science is asked to help. Section 16 concludes the paper.

2. No More General Science?

Some philosophers (e.g., Feyerabend, 2011) have difficulties knowing what science is, and this has led some of them (e.g., as [reported] in Feyerabend, 2011; Psillos, 2012; Kitcher, 2013) to consider perhaps there is no such thing as science but only individual scientific disciplines like physics, chemistry, biology, etc. If there is no such thing as science, then there is no philosophy of general science and this ushers a revolution in philosophy of science to talk only about the philosophy of the individual scientific disciplines (like physics and chemistry) rather than general science. This would mean the past philosophical investigations on science such as empiricism, logical positivism, scientific revolution, etc. are in vein. However, according to Luk (2010; 2016), science is a meta-subject that consists of the common knowledge structures that are found in the different scientific disciplines. While Luk (2010; 2016) would agree that science is not like the specific content of the scientific disciplines like physics, chemistry, etc., he would disagree that there does not exist such a thing called science. According to his view, science encompasses some common knowledge structures (e.g., assumptions, principles, etc.) though the actual knowledge of the disciplines may differ.

While some (science) subject may not appear to have such knowledge structures, sometimes it is a matter of whether the subject is presented as having such knowledge structures or not, rather than the subject can never be able to organize its knowledge structures to coincide with those of (pure) science (and so cannot be claimed to be science). To decide whether a subject is science, each subject needs to be examined to see whether its knowledge structures can be organized similar to those of science. We believe that if it can be shown that the subject can never be organized to be similar to (pure) science or the subject violates some principles or properties of science (as in the theory of scientific study in [Luk, 2016]), then it is legitimate to declare that the subject is not (pure) science. Having said that, the subject may claim it is an applied science rather than a pure science subject. In this case, the deciding criterion is whether scientific knowledge is used in the applied science to solve problems. Note that applied science only needs some scientific knowledge to be used and that the applied science may use other technical knowledge to help to solve the problem instead of just using scientific knowledge. Obviously, the scientific knowledge needs to be derived from some pure science in order for the knowledge to be claimed scientific. So, the scientific knowledge must relate to some theory, model, experiment or physical situation in order to claim that it is scientific.

3. Aimless Science

Rowbottom (2014) suggested that perhaps science is aimless. That is science has no general aim. However, the theory of scientific study of Luk (2016) specified a general aim of scientific study which can be regarded as the general aim of science. The aim is to produce good quality, testable, objective, general and complete scientific knowledge of the domain, as well as monitoring and applying such knowledge (to solve technical problems). Here, scientific knowledge includes the knowledge to conduct experiments, the knowledge of the model and the knowledge of the theory. This general aim is long term, so it may not be accomplished by a single paper or by an individual scientist in his/her life time. It does not necessarily imply that science progress gradually. In fact, science may progress in a haphazard way but eventually meeting the long term goal of science. Luk (2016) finds the general aim of science to be necessary because it is used to constrain how scientific investigations are conducted so that these investigations are guided to achieve the general aim of science. That is why the general aim of scientific study specifies some principles in his theory of scientific study to constrain how scientific investigation is conducted as well as how scientific knowledge is structured.

The significance of the general aim of science is that it specifies the desirable properties of the knowledge that the scientific investigation produces. Arguably some of these desirable properties may never be attainable (for example, completeness) but such properties can be specified in the aim so that science targets to achieve it in the long run. This solves the problem that science has to possess the desirable properties which may not be achievable but yet it is important to mention these properties as they are highly desirable for the scientific knowledge to possess. By specifying the desirable properties in the general aim, there is no need for science or the scientific knowledge to actually possess such properties. Instead, the process of scientific research encourages the scientific discipline to advance toward the general aim of science instead.

4. Exact Science

The model and theory of scientific study by Luk (2010; 2016) (hereafter called Luk's approach) view science only as a best effort approach by humanity, trying to understand the subject matter as much as possible. In other words, science does not guarantee that any scientific discipline will be an exact science as the prediction accuracies depend on many factors (e.g., precision of the instruments, noise, simplifying assumptions and hidden factors). Science is a best effort approach because scientists communicate through publications about how well they can master the subject. They cannot guarantee that any scientific discipline will be an exact science as there is no guarantee for prediction accuracy to be exact. Instead, the theory of scientific study by Luk (2016) can only guarantee that the scientific model will perform better than random guesses according to the principle of modeling accuracy, and the prediction accuracy of random guesses can be extremely low (or far away from exact).

Some (e.g., as mentioned in Smith, 2011 and Watson, 2015) may consider limiting science to natural sciences (perhaps in order for all science to be exact). However, there is no guarantee that all natural sciences are exact sciences. As limiting the object of study cannot guarantee the study to be exact science, there is no need for science to be restricted to natural sciences. Even if limiting the science to natural science can be an exact science, it is also questionable as to why we limit the scope of science in this way, since some non-natural science may also be exact science which is not achieved simply by limiting science to natural science. Therefore, natural science being an exact science is not a defining characteristic of natural science. Furthermore, we have to enquire why limiting science to natural science can lead to exact science, and whether such reasons support the idea that we limit science in this way. Otherwise, it seems arbitrary that we limit science in this way. Therefore, we do not believe that limiting science to natural science is a well supported idea, and we have to find other ways to define science: for example, using Luk's approach.

5. Semantic View of Science

In the semantic view of science (Suppes, 1960), theory is just a collection of models, and a theory seems to be synonymous with models. The semantic view was put forward as a criticism of the syntactic view of science (i.e. logical positivism) which regards theory as an axiomatic system, and models and theories are distinct from each other. While Luk's approach regards theories as distinct from models (Morrison, 1998), his approach does not consider that a theory must be an axiomatic system as many scientific disciplines are incomplete and there may be more than one set of axioms that can generate the entire field of study.

Luk's approach can explain why there is confusion between theories and models in the semantic view. Specifically, Luk's approach indicates that models can be generalized by other more general models. A generalized model may appear in a more abstract arena far away from the corresponding physical situation. For some subjects, a theory may have such an accompanied generalized model so that the theory and the generalized model may appear as inseparable. Since the generalized model is abstract (far away from the physical situations), the generalized model may be regarded as part of the theory. In addition, the generalized model may be used to explain the phenomena, also suggesting that the generalized model is a theory. So, there is some confusion between theory and generalized models. In Luk (2010; 2016), the generalized models are models, and they may be considered as part of the theories or they may be separate from the theories which consist of general properties of the scientific discipline that are applied to specify the (generalized) models. Models by themselves can play the role of explaining phenomena because they may describe the mechanism that generates the phenomena. However, the models are not the same as theories because models do not specify (standalone) individual general properties that are applicable across different situations. Also, models describe processes of generating the phenomena whereas the general properties of the theory may not be part of these processes.

6. Kuhn's Scientific Revolution

Kuhn (1970) suggested that science progresses in a revolutionary manner, abandoning an old paradigm in favor of a new paradigm. His idea was a criticism of the common belief at the time that science progresses gradually. He used physics as an example. Physics is almost like an exact science. Therefore, when there are two competing theories in physics, their models may have very high prediction accuracy (e.g., Rainville et al., 2005), perhaps even 99.99%. So, there is no point in comparing these models and differentiating them by their accuracy. Instead, scientists seek phenomena that can be explained by one theory but not the other, so that the winning theory is more general than the competing ones. Since some theories and models in physics were established hundreds of years ago, a new theory and new models need to take time to find more and more phenomena that the classical theory and models cannot explain or predict. So, physics may appear to progress in a revolutionary manner once there are sufficient phenomena that can be explained by the new theory and models but not by the classical theory or models. However, we believe that there are some other science subjects which may not have very high prediction accuracy unlike physics (e.g., Sarup et al., 2016). So, a competing model may compare its prediction accuracy with the accuracy of the traditional model. Since science is concerned with obtaining general knowledge, the new competing model will also be subject to tests under novel situations but the competing model has to excel in prediction accuracy first before it is subject to tests under novel situations.

Luk's approach does not claim that scientific progress has to be done gradually (as indicated earlier in Section 3). In fact, scientific progress can go backward (in terms of prediction accuracy) even though the long term aim is to advance the scientific knowledge in terms of quality, objectivity, etc., since explanation and prediction (Shmueli, 2010) are different aspects of the (scientific) model. For example, a model may be used to explain how a phenomenon arises but that model may make predictions worse than random (so this may appear to violate the principle of modeling accuracy in the theory of scientific study by Luk (2016) but it is permissible, as long as it is not called a scientific model). That model may only serve to explain (so it is not a scientific model) and it is not used for prediction. Subsequently, a variant of that model may be developed to make predictions, the accuracy of which may be better than random. So, a paper published in science does not necessarily mean that gradual linear advancement (in terms of prediction accuracy) is made in science. Instead, the paper may represent a step towards advancing the understanding even though it may not necessarily mean the advancement is gradual and along the same direction (of prediction accuracy). So, it is possible that a paper may publish a model that achieves a prediction accuracy lower than random, but the purpose of advocating that model is not about the prediction accuracy but to achieve some understanding of the subject matter in order to arrive at a better (scientific) model that makes better predictions.

7. Nature of Scientific Knowledge

Why is scientific knowledge organized into experiments, models and theories? According to Luk's approach, experiments are the only means to access the physical situation which provides the reference of correctness to the knowledge discovered in science. So, experiments are an essential part. This serves to distinguish science from mathematics which may derive its knowledge from the axioms accepted for a particular study. Having said that, it does not mean that scientific knowledge is derived from the senses or experiments as in empiricism (Psillos and Curd, 2010). The scientific knowledge may be the result of the interaction between the scientist's mind (which may distort or transform previous sensory experience without an inverse function) and the implied knowledge from the data observed in the experiments.

Because experiments are mainly used to appraise the scientific knowledge, it is related to both models and theories as such knowledge needs to be appraised. Models are usually more directly related to experiments than theories because the models are applied to experiments by making predictions in the experiments. The success of models is based on whether they make good predictions. Theories are generalizations of models because our aim of scientific study is to look for general knowledge not a set of facts (Kosso, 2007). As a result, theories are put forward to identify the general properties of the models or the experiments where these general properties can be applied to different models and experiments. For example, some of these general properties are assumptions which may need to be true all the time, some of these are principles which are applied to build models and some of these are conditions which specify when the principles are applicable. Some of these properties may be verified by experiments to become physical laws which may in turn be applied to become principles that are used to build models. So, theories, models and experiments are inter-related to each other, but there is an implicit generalization that theories are more general than models, and models are more general than experiments. This implicit generalization is reflected by the basic principle of generalization in the theory of scientific study by Luk (2016).

Unlike mathematics, scientific disciplines cannot guarantee that the scientific knowledge is always correct (Kanazawa, 2008) since the reference of correctness is from the experiments. Also, since science is only a best effort approach as explained in Section 4, scientific knowledge is only provisional, representing our best understanding at present. There is a possibility that scientific knowledge is incorrect and thus it is subject to revision. Having said that, the probability of scientific knowledge being correct is higher than random as required by the principle of modeling accuracy in the theory of scientific study by Luk (2016). Usually, scientific knowledge has a high probability of success. So, some science is like gambling. However, science is not a fair gamble. Instead, the gamble is heavily biased to those who know science, and usually a scientist has reasons to believe why certain outcome is favored. Why is it necessary to ascribe probability to describe scientific knowledge? This is because of the fallacy of induction (Howson, 2000). That is, there is no reason that if something happened a lot of times, it will happen again. To prove that something always happens, we have to carry out experiments indefinitely with infinite resources. This obviously is impossible. So, we have to be satisfied with assigning probability to scientific knowledge to see whether what it predicts will happen, thereby accepting that there is risk in accepting scientific knowledge.

Statistics and probabilities are common methods used in science to make decisions about accepting or rejecting hypothesis. However, they are not the only means to handle decisions in risky situations. Therefore, ascribing probabilities to scientific knowledge is not the only means to characterize scientific knowledge to deal with risky situations. In fact, new mathematics may be developed to assess decisions that are made in risky situations (like Dampster-Shafer theory of evidence). However, the most commonly used methods are statistics and probabilities. We have to see in the future whether other mathematical methods can replace statistics and probabilities in deciding to accept or reject hypotheses.

Using statistics and probabilities to decide whether to accept or reject hypothesis is consistent with the view that science progresses and most scientific knowledge is provisional, which may be subject to change. The finite probability that the decision to reject the null hypothesis is wrong for the experiment means that there may be systematic errors in our model or theory, which may explain why new models or theories are needed. To ascertain that the new model or the new theory is correct, more outcomes in different experiments are needed to be predicted by the new general model or the new general theory, so that the more general model/theory wins over the more specialized model/theory which may not be able to predict accurately the outcomes of all the different experiments. In this way, science favors the more general model/theory.

In applied science, the scientific knowledge is used to solve technical problems. The quality of the scientific knowledge may or may not affect whether the technical problems are solved or not, so the success rate of solving problems may not be affected by the errors in the scientific knowledge. In some applied science, the properties of the problem together with the procedure of solving the problem may guarantee to solve the problem, provided that the used scientific knowledge does not affect the problem solving capability of the solution. Therefore, it is possible that in applied science, the problem may be guaranteed to be solved using the scientific knowledge, so that the applied science appears to be similar to mathematics in which there may be proofs that the problem can be solved by the solution. As a result, knowledge in applied science and mathematics may appear to be similar as they may have proofs of solving the technical problem. In general, some (applied) science may have knowledge which may guarantee the solution to be solved.

Interestingly, the success rate of solving a problem can be related to the prediction accuracy. For example, suppose a solution predicts that it solves the problem 100% of the time, but it only achieves a success rate of 70% in practice. The prediction accuracy of successfully solving the problem is 70% and the prediction error (of success) is 30%. By this argument, an applied science can become a pure science with theories, models and experiments where the model's success rate is its prediction accuracy. In this special type of pure-applied science, it is possible to have proofs of success rate although there may be conditions (e.g., no human errors) of the operation of the solution to guarantee the success rate to be 100%. It follows that most of the knowledge derived from science is risky, but some of the knowledge derived from some special pure-applied science may appear be able to guarantee prediction accuracy and mathematical proofs of such knowledge may appear to be available for such guarantee provided certain conditions are fulfilled.

Typically, pure-applied science of interest to research formulates technical problems with sufficient complexities that realistic solutions with guarantee performance are rare. The technical problems themselves may be highly simplified versions of the real problems. For example, the traveling salesman problem may not consider the altitudes of the cities or whether there are only one way streets to travel. As a result, there may be guaranteed solutions to such idealized problems but whether these solutions are realistic in practice is another concern. In science, the reference of correctness is the physical situation or reality under study, Therefore, the guaranteed solutions to the idealized problem may only serve as approximate or idealized solutions to the real problem. Whether the solution with guaranteed performance has the ultimate prediction capability depends on how well the problem and the solution are modeling the physical situation. So, the real prediction accuracy should be measured in terms of the real problem rather than the idealized problem. As a result, even a proof of performance guarantee exists for a solution does not mean that the prediction accuracy based on the physical situation is 100%.

There are problems where there are no errors when measuring the input or output, so the prediction accuracy is 100%. An example problem arises from the four colour map theorem where the problem is to paint any planar regions of a map so that no adjacent regions are the same color using no more than four different colors. This problem does not require an experiment to see whether the success rate is 100% as there is a (computer) proof. There are also no errors in representing the real problem with the conceptualized problem. So, there are no errors in producing the final result. In this case, experiments are not needed to verify whether the success rate of the solution. As a result, we do not regard such problem-solution to belong to (pure) science. Instead, it is regarded to belong to mathematics. This is because experiment is a necessary part of science, since the reference of correctness of the result comes from the physical situation in science as the scientific knowledge is testable. In this case, the reference of correctness need not derive from the physical situation because the conceptual representation can provide the reference of correctness. In addition, if we regard such problem-solution to belong to (pure) science, we will introduce a paradox in defining science by the model and theory of scientific study. The paradox is that if we consider the previous problem-solution to belong to (pure) science, then (a) experiments are not needed but all stages of scientific development in (Luk, 2010) requires experiments, (b) the basic principle of empiricism (Luk, 2016) is violated, and (c) scientific knowledge is not testable as required by the aim of scientific study (Luk, 2016). Hence, we do not regard such problem-solution to belong to (pure) science. However, such problem-solution can be considered to belong to applied science if scientific knowledge is applied.

8. Scientific logical model?

Scientific models should be able to make predictions so that their prediction accuracies can be measured and compared. However, there is no requirement that all scientific models are mathematical models that operate only quantitatively. It follows that some scientific models can be logical models (e.g., Atwell et al., 2015) as long as the success of predictions can be quantified and measured, and some scientific models are quantitative. This is important as some subjects, which may or may not be considered as science, has only logical models rather than quantitative models, so there is a concern whether such subjects should be considered as science because their models are only logical. Here, we argued that scientific models can be logical models without resorting to whether the underlying subject is science or not, so that scientific models being logical models do not hinder the underlying subject from being scientific.

According to the principle of modeling accuracy in the theory of scientific study by Luk (2016), the scientific logical model is required to make better predictions than random guesses. It does not require that the scientific model makes a better prediction than random each time. Instead, it only requires that overall the scientific model makes better predictions than random, so that it is possible in some cases that a random guess may be correct but the scientific model may be wrong. Having said that, statistical tests are required to measure the reliability of getting better predictions than random. Typically, the prediction needs to deviate from random by a probability of say 95% or even 99.99% in order to accept that the prediction is reliably different from random guesses.

Scientific logical models consist of sets of statements which may be ascribed with truth value, so they may be easily confused with the theory as in the semantic view of science (see Section 5). According to Luk (2010; 2016), scientific logical models are still models and they are separate from theories which just consist of (abstract) statements of properties that have wide spread applicability. Unlike theories, these models describe the mechanism behind the phenomena. While these models contain statements that are ascribed with truth values, their prediction accuracies can still be measured in terms of the percent of the time that they make the correct (or true) prediction. These percentages are usually regarded as probabilities which are compared with those made by random guessing. So, even though these models are logical, it still makes sense to talk about the (prediction) accuracies of these models as suggested by Luk (2010).

9. **Bias in experiment**

The theory of scientific study by Luk (2016) has a principle of objective experiment which does not allow scientists to be intentionally biased to favor certain model or theory over others. However, this principle does not mean that scientists cannot be biased. Scientists can actually be biased in the experiment to favor all the different models or theories, so that each model or theory operates at their best in order to compare their performance (e.g., prediction accuracy). However, the scientist should not be biased to favor some individual model or theory and not favor some other competing model or theory. So, the scientist must either favor none or favor all competing models or theories. Obviously, the scientist may subconsciously be influenced by some bias (e.g., the observer-expectancy effect or those in [Sackett, 1979]). As long as this is unintentional, we may not need to claim that there is misconduct in science even though such bias may affect the quality of the research.

Apart from the principle of objective experiment, the theory of scientific study by Luk (2016) also assumes that scientists strive to make unbiased, accurate observations. Note that these observations have typically happened in natural experiments where the scientists register what they observe (as in some social science). However, since many observations are theory-laden (Bogen, 2014), the scientists are biased in the sense that the observation is interpreted based on the given theory. However, the assumption is that the scientists do not want to intentionally bias the observation so that the observation would favor a particular model or theory over other competing models or theories. The scientist may not have any choice but to interpret the observation based on the available theory. If there is an alternative theory available, the scientist should also interpret the observation based on the alternative theory in order to understand which theory or model is more suitable.

10. Verification and Falsification

In the earlier argument between verificationism and falsificationism in philosophy of science, there is a concern whether science verifies or falsifies a theory. However, can science both verify (Ayer, 1959) and falsify (Popper, 1968) theories? In practice, many scientific papers are about the verification of a theory or model in novel situations rather than existing situations, as in confirmation studies. So, scientists do perform verification but on novel situations to show how existing theories or models can be applied in a novel way in order to expand the generality of the concerned theory or model. Falsification is also done in science (Persson, 2016) but not as often as verification according to Hansson (2006) possibly because good theories and models are not easy to come by. Also, the falsified theories may not be put in papers because the falsified theories may be too absurd or unlikely to consider. As a result, the scientists may focus on discussing the successful theory in their papers rather than talking about the falsified theories, which may explain why Hansson (2006) found more papers about verifications than falsifications.

Confirmation studies are rare in scientific research. This is because usually confirmation studies lack novelty which is required by reviewers of scientific research. So, such confirmation studies may be rejected without getting through to the stage of publication. Confirmation studies may need to add a new twist to the research to increase the likelihood of acceptance by the reviewers. For example, the confirmation study by Rainville et al. (2005) may determine the precision of a well known physical law by experiment instead of just confirming that the physical law holds in an experiment.

11. Micro-Macro Level (Reductionism)

Luk's approach does not exclude the possibility of reductionism (Aerts and Rohrlich, 1998) in the sense that for example, chemistry may be reduced to knowing just physics. Reductionism has the ultimate potential to support the theory of everything (Weinburg, 1992), so that everything can be explained by some fundamental theory at the smallest scale (possibly by Physics). Unfortunately, reductionism is not necessarily implied nor does it automatically follow as a natural consequence. Instead, reductionism depends on whether the micro-level measurements can give rise to models and theories that enable predictions at the macro-level using the given set of measurements. If the micro-level measurements cannot give rise to such models or theories, then reduction may not be possible yet. The discipline may need to wait until some new method of measurement is available that would enable the development of new models or theories that can make macro-level predictions. Therefore, that reductionism cannot yet be done does not mean it can never be done. To prove that reductionism can never be done is difficult because we have to try all possible micro-level measurements to show that no theory or model can ever make macro-level predictions that can be measured. This sounds like we need infinite resources to prove reductionism cannot be done as we have to prove all possible micro-level measurements cannot make any macro-level predictions that can be measured.

In order for reductionism to take place, we require that the micro-level theory and model relate to macro-level concepts and measurements. Without a bridge between the micro-level and the macro-level, it is hard for micro-level entities to make predictions at the macro-level. For example, to reduce Chemistry into Physics, we have to know how a group of molecules behave in a particular phase. So, we have to work out how these molecules interact with each other based on just knowing the individual atoms (physics). Just knowing the concepts may not be enough; we have to relate the measurements at the micro-level and the macro-level so that we can make predictions based on the micro-level theory or model. In order to claim reductionism, we have to show that all macro-level measurements are predicted by the micro-level theory and models, so this is a labour intensive task which is rarely undertaken. As a result, it becomes a matter of belief whether the micro-level theory and model can predict the macro-level measurements by showing some instances that this can be done rather than relying on a full proof.

Even if we have the micro-level theory and model that can make predictions of the macro-level measurement, can this guarantee that the prediction is accurate? Suppose we have a micro-level model that makes accurate prediction of the micro-level events. However accurate the model is, suppose it still has error. This error at the micro-level may be amplified by the (unstable) environment, for example the butterfly effect (Lorenz, 1963), causing the prediction at the macro-level to be different from the actual macro-level event. Therefore, even if we have established a micro-level model that is thought to be able to predict the macro-level event, there is no guarantee that the prediction is accurate or better than by random. Actual tests are needed to ascertain whether the prediction is accurate and reliable.

12 **Scientific Realism**

Scientific realism (shortened to just realism hereafter and see Sankey [2017] for a recent discussion or the handbook chapter by Devitt [2007]) may make different claims by different people but the essential part is that science eventually will arrive at a “true” theory of the reality where “true” may be considered as an accurate description of the reality. In particle physics, most of the particles are not directly observable, so how can we trust what is implied by the measurements in the experiments as an accurate description of reality. At present, Luk’s approach does not subscribe to scientific realism because it is hard to require that the concepts of all scientific disciplines correspond to reality. It is hard in the sense that it is difficult to determine when will all the science subjects be accounted for as some seemingly non-science subject may arrange its knowledge structure to be similar to science, and so such subject may claim itself to be science later, as discussed in Section 2. Also, it is hard in the sense that every science subject needs to be shown to correspond to reality, and very few people have the energy to do that in practice. Finally, it is hard in the sense that it is difficult to prove that the subject does not correspond to reality as scientific knowledge is provisional as discussed in Section 7, so we do not know when do we have the final scientific knowledge and whether the final scientific knowledge of the domain corresponds to reality or not.

As physics is almost an exact science, the prediction accuracy achieved is very high (e.g., Rainville et al., 2005). Therefore, it may not be a surprise that physicists believe their models and theories are accurate and true. However, for some scientific disciplines, the scientific models may have a low prediction accuracy which is the best can be achieved at present (e.g., Sarup et al., 2016). So, scientists in those disciplines may not believe their models and theories are accurate and true. These scientists may be able to readily come up with the shortcomings of their models or theories but these models and theories are the best that humanity can put forward at present. It might be argued that eventually all the models and theories will be accurate and true. However, there is no such guarantee in science (see Section 7). So, Luk's approach subscribes to a weaker position. That is that concepts are intended to be true (or realistic) but whether they are or not we cannot definitively say. All we can be certain is that the concepts are coherent or consistent with our knowledge or measurements, as scientific knowledge has to be ascribed with a probability (see Section 7) taking the risk that it may be false. If it is possible to control the experiments, then scientists may ensure that the laws or principles are emerged from the messy experimental data (as discussed in Luk, 2010), demonstrating that the laws or principles are there in the experiments. However, not all experiments in different scientific disciplines can be controlled precisely, so we have to retract to a weaker position than realism.

While we fall into a weaker position for all scientific disciplines on realism at present, it does not mean that we cannot subscribe to realism for individual or particular scientific discipline. For some scientific discipline, it may be possible that realism is the preferred position instead of the weaker position. Instead of relying on philosophical argument, we may apply the scientific approach to decide whether we subscribe to realism or not. For instance, we may carry out a number of different experiments involving different models from the same underlying theory. These models make predictions. If these predictions are high enough such that the error to perfect prediction is within measurement error and/or noise, then we may claim that the model is accurate enough for us to subscribe that the model and the related theory may be "real" (i.e., the experimental result is one piece of evidence that the model and the theory are real). So, for a number of models applied to different experiments, we can set up a random model to determine whether the model applied to the experiments can attain perfect prediction within measurement error and/or noise. A naive random model may assume that the probability of attaining perfect prediction within measurement error and/or noise is a half (i.e., we do not know whether the scientific model can predict accurately). After five different, independent experiments, if all the experiments show the different models related to the same theory attain perfect prediction within measurement error and/or noise, then the p-value is less than 5%, so at 95% confidence level, we would reject the null hypothesis to accept the random model and there is evidence to support that the theory is "real" (i.e., accepting the alternative hypothesis). In this way, we can apply the statistics and probability as commonly used in science to help us to decide whether the concerned theory is "real". In general, there is no need to restrict the number of experiments to five, the probability of the random model to be a half, and the confidence level to be 95%. More stringent criteria can be set to ensure our decision is reliable. We believe this scientific approach using statistics and probability is an alternative to philosophical argument for deciding whether to subscribe to realism. This statistical approach is coherent with the definition (i.e., 3) of realistic models in Luk (2010), because this approach can specify how many different, uncontrolled experiments are needed to test whether the model is realistic or not whereas definition 3 in Luk (2010) did not specify how many.

Having an accepted scientific procedure to decide whether realism is accepted for a particular scientific discipline does not mean that the decision is final as discussed in the nature of scientific knowledge in Section 7. This is because the decision has a finite probability that it is wrong and we do not have infinite resources to verify that it is correct every time. What the statistical procedure shows is the risk in making the decision and the commonly accepted way to make decisions in a risky situation. There is no guarantee that the decision is always correct. This explains why scientists or researchers focus on the anomalies trying to discover from the errors whether there are general reasons or regularities that explain why the decision is incorrect. If the general reasons or regularities can be found, it may lead to a more general model or theory that may incorporate these regularities or reasons in the generalized model/theory, or it may lead to a specialized model or theory that directly deals with the regularities or reasons in the errors.

Eventually, this represents an advancement of science towards a fuller understanding of the diverse phenomena.

13 **Uniformitarianism**

Luk's approach does not subscribe to uniformitarianism (Gould, 1965) which assumes the constancy of nature so that the natural laws and processes that operate in the universe now have always operated in the past and everywhere in the universe. This is because this assumption makes a giant leap of faith that the universe operates in the same way everywhere in the past and in the future. Since Luk's approach may be applied beyond natural sciences (see Section 4), it prefers a weaker assumption that if the physical situations are similar, then the experimenter would expect similar outcomes from the similar physical situations. This weaker assumption may encounter difficulties with some situations like the butterfly effect (Lorenz, 1963). Here, it is assumed that the similar situations must be similar enough to avoid resulting in different outcomes so that even the flap of the butterfly wings may be considered as an important difference between two different physical situations (in this case two atmospheric systems). Having said that, some scientific disciplines (e.g., geology) may make the uniformitarianism assumption which imply our weaker assumption (that may not imply uniformitarianism), but we believe that not all scientific disciplines will make such a strong assumption. Similar to scientific realism (as discussed in Section 12), we can adopt a scientific approach to determine whether we subscribe to uniformitarianism for some specific scientific discipline. This involves running a number of different experiments which require us to extrapolate the theory or model to work in very different (untested) places and in very different time to test whether they are applicable. Statistical tests help us to decide whether we subscribe to uniformitarianism by observing the *p*-value of the statistical tests similar to scientific realism in Section 12. It should be stressed that the statistical tests do not imply that the decision is final as discussed in Section 12. It merely represents an accepted way to make decisions in risky situation for the time being as scientific knowledge may subject to revision as discussed in Section 7.

14. **What is Science?**

The question "what is science?" (Psillos, 2016) has been a long standing problem in philosophy of science (Chalmers, 2013). While there are many past attempts to resolve this problem, many have failed. One reason may be because it is assumed that science is simple enough to be directly written down as a definition which will then be used to demarcate science. This way to define science has caused proposed definitions of science to either over-generalize or over-specialize. On the other hand, we believe science is complex, so we decided to formulate a model and a theory of scientific study first before we define science. After Luk (2010) specified the model of scientific study, he tried to define science as a subject. Here, we further clarify that:

> science is a common knowledge structure (as expounded in Section 2) that takes the form of theories, models and experiments, which appear across different scientific disciplines. Such knowledge structure and its content are combined to be called scientific knowledge.

What are theory, model and experiment? An experiment corresponds to a physical event in a physical situation in which observations are made, possibly with some degree of control over the physical event. The experiment consists of procedural knowledge on how to set up and conduct the physical event so that similar experiments produce similar results. A model is a description of the physical situation that produces the phenomena observed in the experiments. A theory is a set of general properties of the subject, which are used to specify the models or are directly used to explain phenomena. The process related to science is scientific study which is regarded as a social learning process that revises, produces, monitors or applies scientific knowledge with the aim of securing good quality, testable, objective, general and complete scientific knowledge of the domain, as well as monitoring and applying such knowledge.

15 **Is string theory science?**

Recently, physicists ask philosophers for help (Castelvecchi, 2015) to decide whether some theories in theoretical physics (like string theory or multiverse theory) should be considered as part of science or not. Let us take string theory for example. The problem is that string theory cannot be tested by current technology, so it appears that string theory is not testable. The problem complicates itself as such theory cannot be tested by the technology in the foreseeable future as the energy required to do so is enormous. According to falsificationism or the scientific method, string theory should not be regarded as part of science. Having said that, it is not impossible to test string theory. Philosophers of science have moved away from falsificationism and the scientific method, and they do not consider using them to be fashionable to decide whether string theory is science or not, as many problems/issues are found in them. Instead, Dawid (2013) suggested using Bayesian confirmation theory. This is not completely new in science as probability and statistics are used to make decisions about rejecting or accepting hypothesis. However, Dawid needs to consider a random model in which non-empirical evidence needs to be collected to suggest that the theory is true. Then, use statistical procedure to decide (e.g., 99.99% confidence) that the theory to be accepted or rejected. At present, there are only three pieces of non-empirical evidence (Wolchover, 2015). Even if we use a random model that the probability of a piece of non-empirical evidence suggests the theory is true is a half, string theory is still not over 90% confident that it deviates from the random model. So, string theory is not science by this procedure. However, if this is the case, then it should not have been published by science journals! Similarly, the work in special relativity and general relativity may not have empirical evidence to support when they were published. Should they be excluded from scientific publication by science?

According to the basic principle of empiricism in Luk's theory of scientific study (2016), a scientific theory needs to be directly or indirectly supported by evidence from experiments. So, string theory is not considered as a scientific theory (assuming string theory does not derive the complete Standard Model of particle physics, which is supported by experiments). However, it does not mean that string theory does not belong to science. Instead, string theory belongs to the working scientific knowledge of science according to the theory of scientific study by Luk (2016). Similarly, special relativity and general relativity may also be considered as working scientific knowledge at the time that they were published when they did not have empirical support. The requirement of a theory or a model to belong to working scientific knowledge of science is less stringent than a scientific theory or a scientific model because working scientific knowledge already indicates that the knowledge is provisional rather than established. Instead of requiring experimental evidence to support, working scientific knowledge only needs to show how it is related to existing scientific theories or models to show their relevance to science. This relevance can be demonstrated by showing that theories and models of working scientific knowledge are consistent with existing scientific theories or models, that they generalize existing scientific theories or models, or that they resolve existing theoretical problems in science. So, string theory is part of science but it has not achieved the status as a scientific theory yet according to the theory of scientific study by Luk (2016). To support string theory to be science, Bayesian confirmation theory (as advocated by Dawid [2013]) can optionally be used as a basis to support (numerically) the case for publication or for inclusion to science.

16 **Conclusion**

Luk's approach ascribes probability to scientific knowledge, effectively rendering science like gambling. However, the gambling by science is not fair, and the gambling outcome as predicted by science may need to be explained by science in order to establish a convincing case. Luk's approach explains why scientific knowledge is organized by experiments, models and theories because of the quest for general knowledge. This paper also clarifies the relationship between Luk's approach and various well-known philosophical views (e.g., the semantic view of science, Kuhn's scientific revolution, aimless science, no more general science, verification, falsification, realism and uniformitarianism). It also tries to specify more clearly what is the unwanted bias in experiments, whether scientific models can be logical models, and whether exact science can be guaranteed. Finally, it answers the question: what is science, and it resolves some controversy in theoretical physics.

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