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The Higgs Boson: An Adventure in Critical Realism

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Abstract *The search for the Higgs boson has been like the search of a pirate for buried gold. Like the pirate, the physicist has a map, a conceptual map—the Standard Model (SM) made up of mathematical formulas. Without the Higgs boson in the SM, fundamental particles would be massless. Where could the mass mechanism be? The conceptual map pointed in the right direction. On July 4, 2012 the pirates found their treasure with the help of the Large Hadron Collider (LHC) at CERN. In this article a physicist and theologian ask: could this be critical realism (CR) at work? Could CR constitute a set of presuppositions shared by both physicists and theologians who cannot see the object of their inquiry but employ conceptual models that presuppose the reality of its referent? What role could shared CR play in the creative mutual interaction between science and theology?*

Key words: Higgs boson; LHC; CERN; Science and theology; Standard model; Critical Realism; Postmodern

Science requires faith in order to be science. The form of knowing we know as science rests within a nest of assumptions and hopes about the nature of reality. The assumption that reality is there to be known and that we can know it requires a fundamental trust in the correspondence between the order of nature and the order of the mind.

"Faith is necessary for the scientist even to get started," writes Nobel prize winning physicist Charles Townes, "because he must have confidence that there is order in the universe, and that the human mind—in fact his own mind—has a good chance of understanding this order."[1] Facts are founded on faith, faith that a correspondence exists between the objective physical world out there and the mental picture we hold subjectively in here. The reality of such correspondence cannot be demonstrated within science. It must be provided extra-scientifically. It is provided by faith.

This pre-scientific faith is based on an intuition regarding the order of the natural world and the order lodging in the mind. Alfred North Whitehead describes the pre-scientific conviction. "There can be no living science unless there is a widespread instinctive conviction in the existence of an *order of things*, and, in particular, of an *order of nature*."[2] This pre-scientific conviction regarding order provides the faith upon which empirical experiment and rational reflection constructs its mental picture of the world. Whitehead calls it "faith in reason … This faith cannot be justified by an inductive generalisation."[3]

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Physicist and astrobiologist Paul Davies connects this faith with trust in what is given.

> Sooner or later we all have to accept something as given, whether it is God, or logic, or a set of laws, or some other foundation for existence. Thus ultimate questions will always lie beyond the scope of empirical science as it is usually defined.[4]

Extra-scientific or pre-scientific faith provides the foundation for scientific reason and discourse. Theologian Langdon Gilkey describes scientific inquiry. "For any example of scientific inquiry to proceed at all ... they must, first of all, believe *something* of ontological generality about the character of reality as such and the relation of their minds to it."[5] Just like theology, curiously enough, science includes a large dose of faith seeking understanding, *fides quaerens intellectum.*

To believe that a scientific model can refer to physical reality, counts as an act of faith. It counts as faith because it is an unprovable assumption; or, at least it is indemonstrable through the methods internal to science itself. Science stands on a foundation external to itself, a foundation that elicits trust. The faith of the scientist demands even more trust when he or she posits the existence of a physical reality on the basis of a theoretical model, especially when the empirical evidence for that reference is not yet in. Then, when that empirical evidence comes in like a UPS truck with a delivery of Christmas presents, it provides confirmation of that faith. This is cause for great rejoicing.

Such trusting faith is dramatically illustrated in the search for the Higgs boson. The form this faith takes we will call *critical realism.* According to the trail blazer in the current dialogue between science and religion, Ian G. Barbour,

> *critical realism* must acknowledge both the creativity of man's mind, and the existence of patterns in events that are not created by man's mind ... scientific language does not provide a replica of nature but a symbolic system that is abstract and selective and deals with limited aspects of the situation for particular purposes.[6]

This approach to scientific knowing includes two significant assumptions: that an objective physical world exists independently from human subjectivity and that human subjectivity constructs the picture of that world we hold in our minds. Perhaps this combination is inconsistent or unverifiable. Yet, critical realism appears to provide the operative faith that propels the zeal of scientific researchers who are attempting to turn mystery into knowledge.

The success of critical realism requires the creation of conceptual models, frequently mathematical models, to assess data and organize measurements. Physical cosmologist Stephen Hawking refers to model construction as *model-dependent realism.* "The naive view of reality therefore is not compatible with modern physics ... we shall adopt an approach that we call model-dependent realism."[7] Hawking contends that "a physical theory or world picture is a model (generally of a mathematical nature) and a set of rules that connect the elements of the model to observations."[8] Our term here for what Hawking describes is *critical realism.* Research scientists place conceptual models between empirically derived data and what they deem actually to be the case with physical reality. According to Barbour,

> models and theories are abstract, symbol systems, which inadequately and selectively represent particular aspects of the world for specific purposes. This view preserves the scientist's realistic intent while recognizing that models and theories are imaginative human constructs. Models, on this reading, are to be taken seriously but not literally.[9]

By plugging empirically derived facts into the model, the researcher hopes to generate fertile new directions to take his or her research. The model method permits research to press forward when the naive option is unavailable. This pressing forward with a fertile model is what we have seen in the search for the Higgs boson.

In what follows we will ask six questions: (1) does critical realism appropriately describe the search for the Higgs boson? (2) just what does critical realism presuppose and suppose? (3) does critical realism belong in the modern or postmodern camp? (4) is verisimilitude compatible with critical realism? (5) should theology adopt a postmodern methodology? and (6) what role can critical realism play in the interaction between natural science and Christian theology?

1. Does critical realism appropriately describe the search for the Higgs boson?

The God particle? The trigger on the Big Bang? This is how scientists described the Higgs Boson while uncorking their champagne bottles to celebrate the new discovery. Nearly five decades ago physicists predicted—hypothesized—that there must exist in the physical world a particle responsible for *imparting* mass to other particles. The standard model (SM) of fundamental particles and forces, like a puzzle, had a piece missing. On July 4, 2012, researchers working with the gigantic high-energy particle accelerator, the Large Hadron Collider (LHC) at CERN in Switzerland, built especially to find that missing piece if it existed, announced they had found it.[10] The standard model required the theoretical inclusion of such a component, even though it had not yet been empirically detected.[11] When detected, it was a moment to celebrate. Excited scientists greeted one another with "Happy god particle day!"[12] Just how might critical realism help describe this?

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More specifically, the *standard model of fundamental particles and forces* describes what makes up ordinary matter. Among the particles are the electrons; the up quarks and down quarks that make up the protons and neutrons in atomic nuclei; neutrinos; and two sets of heavier particles that emerge in particle collisions.[13] Three of the four fundamental forces are involved: the electromagnetic force, the weak nuclear force, and the strong nuclear force. Conspicuously absent was an account of the gravitational force.

The problem with the standard model in its initial development was that it is a theory for particles with zero mass. The mass question remained unanswered. Somehow, it seemed, mass would have to emerge from interactions of the otherwise massless particles. This led to the hypothesis that the empty space would be filled with a field, a scalar field, that is always present, and named the Higgs field—after Peter Higgs—and associated with a quantum, the Higgs boson. When particles interact with the Higgs field a mechanism—the Higgs mechanism—activates. The mechanism requires the Higgs field to choose a specific minimum energy value, from a ring of equally good minima, and then couples the Higgs field to other quantum fields.

The concept of the Higgs field was introduced to break the symmetry of one of the mathematical theories used in the standard model, thereby allowing the particles to gain mass. Could this hypothesis lead to an experiment and a confirming observation? If it fits the mentally constructed model, does it also fit empirical reality?

Specifically, the conceptual model of the Higgs boson is a mathematical model that allows for: (a) the classification, identification and formulation of symmetries developed in the standard model for massless particles to continue to be operative; and (b) the interactions that occur between the fundamental particles carrying charges, with strengths proportional to the sizes of the charges, and transmitted by bosons, known as quanta of the fields set up by the charges to continue to be operative. Note that (a) and (b) are known as gauge theories with spin-1 vector bosons Then, we move to an important convenient reality: (3) the mediation of interactions governed by (a) and (b) by setting up the spontaneous symmetry-breaking scalar field. This allows the particles to have their experimental values for mass, without disrupting other important properties of the standard model that work, and are the basis for different parts of the theory.

Thus, according to the conceptual model, mass is generated and gauge symmetry conserved by spontaneous symmetry-breaking through the introduction of the Higgs boson. The theoretical requirement of retaining gauge invariance indicated that a particle like the Higgs boson must be there. Beginning in 1964, what turned out to be a near half century hunt began in order to find it. Although no one had ever detected a Higgs boson, the physicists followed their conceptual GPS in search of it. They had faith that they would find it.

Let us map the process.[14] To begin scientific inquiry, a problem (correcting, testing, validating, or pioneering) is selected and defined, with the implicit intent that the information and work must be verifiable, that it can be replicated by other scholars and will be judged in the peer-review process. In the case of the Higgs boson, the hypothesis, theory, peer review, publications, and extensive study had already occurred and continued to be at the forefront for this theoretical particle. By *theoretical* is meant a clear and distinct mathematical formulation—a conceptual model—from which predictions can be made and information obtained that validates what is already known. The Higgs boson is a case of theory generating a progressive research agenda. Theory leads experiment, which in particle physics can be the norm. The big news is that a particle, hopefully the Higgs boson, as predicted, has now been detected.[15] What had been imagined has now been found.

Maybe. As of this writing, it has not been fully tested and validated—reconfirmed—which means there are a number of next steps so that the particle's decay and production activity becomes more well known. So, from the outset there is no recipe-like scientific method that comes to a final conclusion. The hypothesis for the boson is to give other particles mass as the quantum (excitation) in what has become known as the all-permeating Higgs field. The investigative problem now becomes one of validating the boson's existence, by producing *enough* high-energy collisions to generate *enough* bosons within kinematic range, so that they can be replicated, measured, and compared to the theoretical predictions. "Although its measured properties are, within the uncertainties of the present data, consistent with those expected of the Higgs boson, more data are needed to elucidate the precise nature of the new particle."[16] Empirical data confirm or modify the model, and the next experiment is generated.

What researchers found on July 4, 2012 was a particle with zero spin and positive parity, exactly what previous physicist prophets using SM had predicted. Now, LHC experimenters are looking forward toward discovering something beyond the standard model's "cast of particles. Some theories predict that other Higgs bosons lurk over the energy horizon."[17] Does this suggest we should refer to what we know as "a" Higgs Boson instead of "the" Higgs Boson? Answers generate new questions, unendingly.

The Higgs boson experimental search is a clear case of Hawking's model-dependent realism and what we call *critical realism* or CR. The boson was predicted to exist for the purpose of giving mass to particles in the standard model. The standard model is a mathematical formulation that describes coherently how the various particles in it fit together. Empirical evidence had been provided for particles with mass in SM; but the theory would remain malnourished until it could imbibe evidence for particle mass. The Higgs boson mathematical structure was needed, paraphrasing Hawking, to set the rules that connect the particles in the model to experimental reality. Or, as Robert John Russell writes, "the Higgs field explains the variety of masses of the fundamental particles in the Standard Model."[18] A clear case of CR at work.

Is the Higgs boson discovery unique? By no means. Let's remind ourselves of what scientists do as a matter of routine. The numbered items below have been generalized and provide some overall thinking normally used by physical scientists after reviewing and knowing what literature, if any, has been published regarding the subject problem.

(1) *Collect data.* In science in general, data (as much data as possible) are collected from observations of organized experiments under controlled conditions and classified for exploratory examination. Data regarding the Higgs boson, specifically, are obtained by the collision of high-energy particles that are actually projectiles, proton with protons or antiprotons depending on the collider. The energy created by the collision of the protons has to be much larger than the mass of the Higgs particle for its production. The greater the energy the more production obtained and the more details revealed. However, if raw data consist of point-like particles produced from colliding high-energy protons beams, emitting discharged sparks or light flashes, observed with sophisticated accelerator detectors, and only lasting 156 trillionth of a trillionth second before decaying into other particles, as in the detecting of the Higgs boson or Higgs-like boson indicated above, collection of Higgs data requires a comprehensive understanding of experimental observations and theoretical predictions.

Data collecting is not random. Researchers know in advance where to look. The specific list of data sought is generated by a prior conceptual or mathematical model within which the data would fit. Or, to say it another way, facts are theory laden. This means an "anticipation of observation" relationship exists for cause and effect between experiment and theory in the Higgs validating process in particular, and any scientific investigation in general. There is a theoretical necessity for the boson and the presupposition is there is a particle to be discovered. However, not naively since the mean lifetime is theoretically predicted to be non-existent to our five senses, therefore the boson has to be determined indirectly.

Do the findings produced in the experimental apparatus, LHC in the experiment for the Higgs boson, act as anticipated using the theoretical predictions within the required statistical significance level to be considered a discovery? Indeed, CERN's observations pointed to the existence of the Higgs or Higgs-like particle because the mass observed was within the required theoretical prediction level. Along with this activity is the question of background effects: expected decay and production activity besides that which is to be studied and which might have caused interference. All the decay and production activity have to be questioned, correlated, and understood. Scientists use experimental insight, imagination, creativity, judgment and vision to collect desired data. That is, there are no constraints on the scope of the investigative process except the intelligence, perceptiveness and skill of the scientists themselves.

In the Higgs case, proton beams accelerated to speeds near the speed of light were arranged so they would collide. The particles found from the collisions and believed to be the Higgs or Higgs-like bosons rapidly decayed (again the boson's expected mean lifetime is 156 trillionth of a trillionth second). Therefore, without direct observation, inferences and conclusions had to be drawn about the boson's existence and properties from its decay particles. This leads to a metaphysical implication, says John Polkinghorne: "*reality is not the same as naïve objectivity*."[19] That is: "the guarantee of reality is not objectivity but intelligibility."[20] In this case the reality we are referring to is not available for sense perception. However the Higgs boson makes physical sense, even though it is being detected from its decay particles and not directly, because it provides a meaningful theory for imparting mass to the particles in the Standard Model, and allows the Model to still retains its mathematical structure. SM is a theory in which the particles have zero mass; however, in reality most particles have mass and the Higgs boson supplies the mechanism for their ontological structure.

(2) *Examine and correlate data.* The data gathered are analyzed and studied to determine patterns by which inferences may be drawn and predictions made for the behavior of the system. In the Higgs study, the quantum debris of trillions of particles that resulted from the proton beams colliding were examined for those that had the mass of the Higgs (125–126GeV), that is, 125–126 billion electron volts. The examination involves a comparison of the observed decay paths after a collision with the decay paths simulated with computers, and mapped for the Higgs mass to determine if there is a match. Conceptual models are constructed for the process and if a match is found, Higgs has been fulfilled, but not entirely. Although a new particle seems to have been discovered which behaves like a Higgs boson, background and pile-up activity can be significant, so more data

have to be collected and analyzed to test for consistency and rule out competing modes of production and random fluctuations. The problems for the boson had been worked out in 1964 as theoretical answers to various questions that were raised about mass-less particles. The experimental data obtained by the CERN groups was due to theory and techniques devised for finding the boson from the SM calculations, by working with the interpretive presupposition that discovery begins with a pre-understanding already present in SM through the Higgs process. The metaphysical implication is: "what is 'reasonable' cannot be decided by pure thought alone but only by looking for evidence of what is actually the case."

(3) *Develop and test hypotheses*. After studying numerous data, a mathematical statement or physical picture may be developed, as a hypothesis, which guides future experiments into the behavior of similar systems under different conditions. The preceding statement had been developed for the Higgs boson not from experimental data, but by Higgs from his theoretical understanding of how the particle needed to impart mass in the Standard Model should function. Then he applied the mathematical framework to show details of his understanding in the 1964 paper. In theoretical work hypotheses can be developed, worked and reworked, and studied many times before data is obtained from an experimental procedure that agrees with the theoretically derived quantities. The Higgs boson is the present example. And the same cooperation will continue to guide future theoretical and experimental developments with the success of the July 4, 2012 discovery at CERN. However one might ask: what is the relationship of the elementary particles within their mathematical framework, beyond the mind of theorists and particle physicists, to activities in the daily experience of people in all walks of life?

(4) *State a theory*. After the hypothesis has been subjected to experimental verification numerous times, and the predictions it provides for the behavior of theoretically derived quantities under changing conditions are found to be qualitatively accurate, it is called a theory. However as stated previously theory can lead experiment. In that case, mathematical premises may be developed to predict certain properties of the subject entity. Later it may be shown experimentally that the predictions were correct or that more detail investigation is required. This mutuality means a theory may be revised if different and more detailed data from experiments are collected which gives a better conception of behavioral variations and conditions. That said experiments underdetermine theories. And causality can lead to errors when determined from limited data since both theories and experiments are based on human experience and understanding which is finite. And theory and experiment must interact together for an interpretation of reality. Otherwise experiment without theory is void of interpretation, and theory without experiment is unsubstantiated hypothesis.

The circular or spiraling movement between theory and data are key. The theory generates the direction the next experiment should take, while the experiment confirms or modifies the theory. The measure of a good theory is its fertility, its fruitfulness, its generativity. "The value lies in the program's fruitfulness in opening up constructive insights (new knowledge)," writes Philip Hefner. "This capacity to stimulate new insights, or lack of such capacity, is the chief criterion for judging proposed theories."[21]

(5) *Submit findings for peer review and publication.* This guideline is most important because with rare exceptions the practice of science is carried out in an implicit "college" of scientists. By college is meant a self-governing association of scholars engaged in the pursuit of truth in a given scientific discipline. I remember the statement in Daniels and Alberty.[22] "Science is based on truth, and [scientists] cannot AQ2 allow [themselves] to be influenced by any prejudice. Science has become such a potent factor in our national and international affairs that the scientist now faces a social responsibility extending far beyond the laboratory." Scientists believe that the peer review process for their work is one factor in meeting this responsibility, since it helps maintain integrity and upholds quality and at its best reduces errors and fraudulent activity. And since peer review is an evaluative process for the overall scientific merit of a work by an "expert" independent colleague or group of colleagues, it acts as a method of checks and balances. Once the work has gone through this process and is deemed acceptable, the editor(s) of the scholarly journal who rely on the process publishes the work.

The public sharing and publication phase insures inter-subjective re-analysis leading to confirmation or disconfirmation. Because we cannot measure the claims against the physical reality itself, we can only ask independent researchers to repeat the experiment. This process may find weaknesses in data gathering or coherence in the model; or it may produce corroboration. Corroboration does not establish apodictic truth, but it does add to the relative plausibility of the claimed explanation. Without critical realism operating at the presuppositional level, this approach to making claims about physical realities unseen would not count as knowledge.

But where does the future of public sharing and publication lie in light of the changing landscape as explored in the March 28, 2013 issue of *Nature*? Scholars must have a central role in this question, and one way might be a position on how we choose to balance and disseminate guiding, substantive, and cutting edge research. And, engaging and weighing in on the implementation of changes keeps scholars and their organizations as stakeholders on the impact made by the future delivery and carrying out of services.

As previously announced, we are asking six questions: (1) does critical realism appropriately describe the search for the Higgs boson? (2) what does critical realism presuppose and suppose? (3) does critical realism belong in the modern or postmodern camp? (4) is verisimilitude compatible with critical realism? (5) should theology adopt a postmodern methodology? and (6) what role can critical realism play in the interaction between natural science and Christian theology? Our answer to the first is affirmative. Still, more needs to be said. So, we will proceed to our second question.

2. What does Critical Realism presuppose and suppose?

What is *critical realism*? CR makes an epistemological claim regarding just how we know the physical world that we cannot see. As a form of realism, it includes a methodological set of assumptions presupposing that an objective world actually exists and that we can know it through inquiry. As a form of realism, it presupposes that it is possible to know the external world as it is, independent of the human mind. As critical, it presupposes that human subjective analysis and construction contributes to what we deem to be knowledge. Our knowledge is more than mere perception; knowledge requires critical reflection on perception. Scientific critical realism assumes that mature theories are approximately, though not absolutely, true and that their postulated entities actually exist. Oxford's late Arthur Peacocke put it this way:

> the basic claim made by such a critical scientific realism is that it is the long-term success of a scientific theory that warrants the belief that something like the entities and structure postulated by the theory actually exists ... It must never be forgotten that the realism is always qualified as 'critical' since the language of science is ... fundamentally metaphorical and revisable, while nevertheless referring.[23]

CR replaces naïve realism. Naïve realism is a form of empiricism which relies directly on sense perception for apprehending reality. We can see the object we are studying. We perceive it. We can measure the truth or falsity of claims by comparing the claims to the reality itself. This brand of realism presupposes that truth takes the form of correspondence—that is, what we claim to be true must correspond to the reality to which it refers.

Gilkey breaks naïve realism into component parts: it assumes

> (1) that ontological entity and scientific explanation are isomorphic; (2) that this explanation uncovers the entire mystery of the object, so that no other explanation is either necessary or possible, and (3) that any alternative explanations, or modes of inquiry, are competing explanations on the same plane, unequivocally false, and thus cancelled out by the correct explanation.[24]

The naive realist can retain such confidence in his or her own claims because the reality to which these claims refer corroborates them. The claims are true because they correspond to what is really there. Just look and see!

But, what happens when the reality we refer to is not available for sense perception? What happens when only indirect evidence is available? What happens when we cannot measure claims directly against their reference to see if they correspond? A fundamental particle such as an electron or the Higgs boson cannot be perceived, but its effects—allegedly—can be measured. Is it actually there? Much of physical reality is simply not accessible to the senses of the scientist, yet the scientist believes it is there.

To assemble and assess data, the scientist creates a conceptual model, often a mathematical model, within which measurements are organized. We saw how Hawking refers to such model construction as *model-dependent realism.* As we saw in the case of the standard model of fundamental particles and forces, by plugging empirically derived data into the model, the researcher constructs an expectation of what might be found. New experiments get planned. Confirmation or disconfirmation propels further research. The model gets corrected and new research agendas get generated. The presupposed structure of critical realism provides the confidence that the model can be fertile and progressive. Critical realism functions like a basic faith commitment, which permits if not inspires the pursuit of new knowledge. Do we have here an instance of scientific faith seeking understanding?

The sociology of knowledge adds another factor: theory construction and model development are the product of the human imagination. The imagination at work is shared, shared by the cultural and linguistic context within which it is formulated. Scientific theorizing is as context-dependent and historically relative as all other human thinking. More specifically, the morphology of scientific paradigms is historically contingent, subject to social location and power struggles.

Acknowledging the role played by imagination and social influence on theory construction puts any form of realism at risk. Recognizing the inter-subjective factors in model adoption could lead to reducing scientific theory formation to mere social construction, to mere subjectivity. Because the evaluation of scientific claims cannot be measured directly against their reference, one might be tempted to adopt an instrumentalist view. One might describe scientific claims as fictions, even if useful fictions. The assumption that reality is referred to in critical realism attempts to prevent this reduction; but it operates at the presuppositional rather than the suppositional level. "Critical realism avoids naive realism, on the one hand, and instrumentalism, which abandons all concern for truth, on the other," says Barbour.[25]

One might surmise from this that our epistemological problem here is discerning whether or not an objective reality out there exists. This could be misleading. The issue is rather: Just how much confidence can we have in what we deem to be scientific knowing? According to Willem B. Drees, editor of *Zygon*, what is at stake is "not debates about the existence of 'reality out there', but debates about the quality of our knowledge."[26] The research scientist need not solve the philosophical problem of reference. He or she needs only to progress in our knowledge of a specific matter. And if the assumption of reality-reference suffices to make this happen, then so be it.

CR implies that construction and discovery come together. On the one hand, as imaginative constructions, scientific claims fall short of literal truth and, therefore, future revisions of today's knowledge are expected. It means, according to John Polkinghorne, "one cannot claim the achievement of science to be that of the attainment of absolute truth,"[27] since revisions occur from time to time and may be radical. Still, on the other hand, scientific knowledge relies on discovery, discovery of what is really there. According to laboratory researchers, discovery cannot be reduced to something merely devised or invented or of human construction. That is the reason particle physicists spoke of *discovery* on July 4, 2012; and the Higgs-like particle found is thought to be a discovery rather than an invention. The concept of the Higgs boson was the product of constructive thought, to be sure; but the empirical confirmation of what the model predicted was the product of discovery. That discovery cannot be reduced to the construction, if one is a critical realist.

A researcher would not want to be told his or her discovery was itself *constructed* by human ingenuity. Rather, it was *discovered* by human ingenuity. The "*Collect data*" section above demonstrates the specific role played by human ingenuity in model construction and fact collecting. In addition, the foundation for the Higgs boson in the standard model is an excellent example of relating a mathematical and theoretical understanding to the physical nature of reality. "Critical realism recognizes that it is still only the *aim* of science to depict reality and that this allows gradations in acceptance of the 'truth' of scientific theories."[28] It is a realist position since scientists presume that although the aim is to describe the physical world, it only occurs with a continuity of development and understanding of theory and experiment. "The realism is always qualified as 'critical' since the language of science is … fundamentally metaphorical and revisable, while nevertheless referring" to the cause, effect, and creative mutual interaction of theory and experiment.[29]

3. Is Critical Realism modern or postmodern?

CR is modern in the sense that it relies upon rational discourse to describe physical reality, a single universal physical reality. It is postmodern in the sense that it is non-foundational—that is, it recognizes that its view of reality is lodged in creative human mental processes and is, therefore, perspectival, relative, and changing. Let us explain.

How can we decide whether critical realism is modern or postmodern? Let us get specific. Many interpreters of Western intellectual history put the pivot point between what is modern and what is postmodern on the relationship between subject and object. They define modernity in terms of the Cartesian split between subject and object; and they define postmodernity in terms of the overcoming of this split. Others find the pivot point to be the foundation for knowledge. They describe premodernity and modernity as foundationalist with postmodernity as non-foundationalist.

According to this second view of the pivot, premoderns established their epistemological foundation on authority, such as the authority of scripture or the authority of the priestly tradition. Moderns established their foundation either on pure reason or sense experience. Both the premodern and modern foundationalist approaches are now outdated. Outdated foundationalist epistemologies presume a correspondence theory of truth—that is, truth occurs when what is subjectively thought corresponds accurately to what is objectively authoritative or real. Knowledge consists of mental photographs of what is real "out there." Reality belongs to the object. Subjectivity bows to objectivity. The objective realm is where the foundation for knowledge is laid. Postmoderns, in contrast, get along quite well without such a foundation in objective reality.

Might we suggest that these two pivot points are actually only one? Might we suggest that, according to the modern foundationalist, objective knowledge allegedly provides the foundation for any knowledge thought to be true, at least until confronted by the postmodern challenge? By denying the privileged status of the objective realm, postmoderns reconstruct the relationship between the subjective and the objective.

With this in mind, Nancey Murphy contends that the critical realist position rests upon a confusion. On the one hand, critical realism takes a strictly modern foundationalist position. On the other hand, it tries to incorporate a postmodern or postfoundationalist recognition of the sociology of knowledge. The confusion surfaces when advocates of CR claim this position lies at a midpoint between naive realism, on the one end, and relativist subjectivism, on the other. A "source of the confusion is the claim that critical realism is a *middle* position between naive realism and the sociologists' position. However, there can be no midpoint between positions that are not located in the same space."[30] We saw this spectrum articulated by Ian Barbour above. Murphy rejects this Barbourian analysis. She contends that modernity and postmodernity occupy different spaces; and critical realism should sit in only one space rather than straddle the two. Just how do we identify these separate spaces, the modern and the postmodern? To that we now turn.

As the postmodern mind pivots, it can step away from modernity in one of two directions: deconstructionism or holism. Both "isms" are attempts to overcome the split between subject and object; and both pursue knowledge without reliance on an objective foundation. *Exclusive* reliance on an objective foundation, that is. For the postmodern, the subjective does not bow to the objective.

According to the deconstructionist direction, what we take to be knowledge is a construction of human subjectivity, especially group or contexualized subjectivity. Knowledge is not a mental photograph of what is objectively real. Rather, it is generated by human imagination. The so-called objectively real–the thing in itself or *Ding-an-sich*—cannot be accessed in its purity. The object cannot stand in judgment over our mental pictures to determine whether they are accurate or true. All knowledge includes subjectivity, perspective, pre-understanding, pre-judgment, context, social location, self-interest, and the will to power.

The deconstructionist treats cognitive claims as texts, texts to be critically interpreted. Critical interpretation begins by severing the connection between the text and its purported object. Even if the claim of the text refers to an object that is extra-textual, it is the text itself that gets deconstructed. Deconstruction dislodges the codes of authority and foundational assumptions such as referential truth claims. Reversal and displacement are exacted. The reversal consists of inverting the text's implicit hierarchy so that the term previously suppressed in the binary opposition becomes powerful. The displacement—also called transgression or reinscription—keeps the hierarchy unstable so as to avoid reinforcing the dynamics of the old hierarchy in reverse.[31] Deconstruction is a dynamic ongoing hermeneutic, never resting in a final or static state of interpretation. Whatever the deconstructionist interprets gets inverted. This inversion counts as *critical* in the deconstructionist method.

Niels Henrik Gregersen and Wentzel van Huyssteen applaud the deconstructionist variant of postfoundationalism for including the human subject in its version of postmodern epistemology.

> Postmodernity has rightly unmasked the illusions created by epistemological foundationalism. We now know that any issue is always seen from a particular interpreted point of view, and that our epistemic practices therefore constitute contexts in which our very participation is a precondition for our observations.[32]

We might ask Gregersen and van Huyssteen: have you retained the objective or referential component? Or, do you ask objectivity to bow to subjectivity? Do you ask correspondence to bow to coherence? Do you ask reference and correspondence to bow all the way out?

As we have said, the pivot from modernity to postmodernity opens two gates. The first is desonstructionism. The second is holism. Philosophical theologian Nancey Murphy opens the holism gate. She declares, "perhaps the clearest and cleanest break with modern thought is the replacement of foundationalism by holism."[33] Holism fits multiple referential claims together into a conceptual web, which reinforce one another. The correspondence theory of truth is not replaced but complemented by a coherence version of truth. Coherent truth is not apodictic or absolute or dogmatic; rather, it weighs what seems more coherent assemblages of data over against what seems less coherent. Claims are tested "as a combination of coherence and empirical adequacy … given a stable conceptual system, truth is in part a function of the way the world is."[34] Murphy seems to want both coherence and correspondence, both conceptual construction and empirical reference. This is what the critical realist wants, even though Murphy has distanced herself from this brand of realism.

As we see, the holistic approach incorporates both the object and the subject of cognitive claims. It acknowledges that cognitive claims are generated by human imagination, while reference to objective reality is retained. Any description of an objective referent must include the subjective interpretive factors in a single holistic understanding of interpretation.

What is happening here? Reference to the external or objective world is retained by the holists; while subjective constructivism is acknowledged and declared integral to human knowing. We ask: does the realism in critical realism require a return to the modern; or can it be incorporated into a postmodern epistemology? Are we asking to have our cake and eat it too?

Van Huyssteen offers a constructive proposal to explain postmodern rationality. A *postfoundationalist model of rationality* recognizes that

> while we always operate in terms of concepts and criteria that appear within a particular culture, we are nonetheless able to transcend our specific contexts and reach out to more intersubjective levels of discussion. Over against the relativism of a nonfoundationalist 'many rationalities' view, a postfoundationalist model of rationality aims to show that scientific reflection, as a highly contextualized reasoning strategy, can indeed be a potential and reliable source of knowledge that not only transcends the cultures in which various sciences first appeared, but can also epistemically relate to broader and different notions of rationality.[35]

Or, "the thesis that what is rational to believe or do is relative to a particular situation should therefore not be confused with the thesis that rationality itself is relative."[36] Is he saying here that rationality transcends context because it is referential? If so, then he stands next to Murphy. If not, then he stands with the deconstructionists, the relativists.

It appears that Van Huyssteen wants is to combine the unavoidable relativism of postmodern subjectivism with objective reference. It is not clear just how these two fit together, however. Perhaps van Huysteen is describing his goal rather than his accomplishment. Nevertheless, his postfoundationalist model seeks to incorporate both subject and object within a single holistic model. "Once we have acknowledged the cultural, linguistic, or social context of a claim, the point remains that many claims make assertions about some state of affairs that is independent of those claims."[37] Critics may ask: can one have the cake and eat it too? The deconstructionist position answers, no; the objective must bow to the subjective. The holist model answers, yes; both the objective and the subjective belong together in a single act of knowing. Whether contemporary physicists know it or not, they would prefer the holist over the deconstructionist alternative. Without the presupposition of reference, the physicists would never have found that illusive treasure, the Higgs boson.

We would like to tender the following conclusion: CR in science is modern in the sense that it relies upon rational discourse to describe objective reality, a single universal physical reality. It is postmodern in the sense that it is nonfoundational—that is, it recognizes that its view of reality is lodged in creative human mental processes and is, therefore, perspectival, relative, and changing. A skeptic might contend that the real and the critical in critical realism are incompatible or noncompossible. Regardless, this seems to be what is presuppositionally operative in a science such as particle physics. In the case of the Higgs boson, the presuppositons of critical realism seem to have been fertile.

4. Is verisimilitude compatible with Critical Realism?

Some proponents of critical realism invoke the principle of verisimilitude, which suggests that theoretical models progressively increase their approximations to objective reality. Roman Catholic fundamental theologian Bernard Lonergan, for example, hints at verisimilitude when contending that

> the critical realist can acknowledge the facts of human knowing and pronounce the world mediated by meaning to be the real world; and he can do so only inasmuch as he shows that the process of experiencing, understanding, and judging is a process of self-transcendence … a verified hypothesis is probably true; and what probably is true refers to what in reality probably is so.[38]

The late Ernan McMullin offers a similar hint. Scientific realism claims "that the long-term success of a scientific theory gives reason to believe that something like the entities and structure postulated by the theory actually exists."[39] If we want more than a mere hint, we turn to John Polkinghorne, who builds verisimilitude right into his version of critical realism. "Our understanding of the physical world will never be total but it can become progressively more accurate."[40] Or, "science and theology have this in common, that each can be, and should be, defended as being investigations of what is, the search for increasing verisimilitude in our understanding of reality."[41] What is meant by the term *verisimilitude* is "the attainment of increasingly closer approximations to the truth about physical process."[42]

Now, we might ask: is verisimilitude compatible with critical realism? How might one go about testing to find out? If what is purported to be real is inaccessible except through the conceptual model and data collecting, one cannot measure greater or lesser degrees of correspondence between the model and its referent. One can compare models to see which incorporate more data or provide superior explanations or generate more progressive research, but objective reality is not available to decree which is closer to reality, so to speak. The fact that some theories are replaced by more adequate theories does not in itself confirm the principle of verisimilitude. "Many successful scientific theories in the course of time have been replaced by other successful theories, therefore, success is no reason to believe that something like the entities and structures postulated by the theory really exists," says Niekerk.[43] Van Huyssteen, among others, would demure on versimilitude. "Even if we are committed to the view that later theories are better theories, it does not have to imply to a closer-to-the-truth position."[44] We conclude that even though more adequate theories can be distinguished from less adequate theories, verisimilitude is not the measure.

5. Should theology adopt a postmodern methodology?

Should today's theologian adopt a modern or postmodern approach to theological reflection and explication? Nancey Murphy, among others, recommends the holist postmodern approach. "Non-foundational theology employs holist justification, which seeks the relation between a disputed belief and the web of interrelated beliefs within which it rests."[45] But our topic here is critical realism, which seems to be a hybrid of modernity and postmodernity, at least according to Murphy' analysis. Before we get to our elected question, let us pause for a moment to reflect: should theology adopt a postmodern epistemology?

Murphy describes her postfoundationalist holistic theology as reflection on religious experience, with the Bible providing data or facts—actually privileged data or facts. "First, postmodern conservative theology must maintain some special role for Scripture over against experience as authority for theology; second, it must provide for special acts of God; and third, it must provide for the possibility of making truth claims for Christianity."[46] With the hermeneutical privilege granted to scripture in mind, let us follow Murphy's lead on reflection on experience in light of biblically based core beliefs.

Recognizing the circular relationship between theory and facts in science, so also in theology core beliefs provide the framework for interpreting human experience in general as well as biblical data.

> The hard core of a research programme in systematic or doctrinal theology, therefore, will most likely be one's non-negotiable and most general understanding of God and of God's relation to the created order. The doctrine of the Trinity functions nicely as a core theory for classical orthodoxy, since all of the rest of the Christian doctrines can be unified by means of their direct or indirect relations to one of the persons of the Trinity.[47]

Core doctrine provides the theory that reflects on biblical facts, just as the biblical facts are already theory-laden or doctrine-laden. This is a circular interaction, to be sure; but it is still a progressive movement toward expanding or deepening knowledge. "There is always a degree of circular reasoning involved, but it might be called virtuous rather than vicious circularity."[48]

John Puddefoot accuses Murphy of relying excessively on reference or empirical verification of theological claims. Murphy "is trying to place the emphasis for theology and science upon yet another version of empiricist foundationalism." In the place of appeal to referential correspondence, Puddefoot places observations about personal faith and the Christian community, the church: "I would want to emphasize the acts of personal judgment and communal affirmation and reaffirmation that underpin all the knowledge we have of all things, not on the basis of correspondences mysteriously discerned between theories and their referents."[49] It appears to us that Puddefoot has eliminated the realist component and replaced it entirely with personal testimony, with a strict appeal to subjectivity.

Similarly, Grant Gillett believes he parts from Murphy by emphasizing the indispensible self-involvement of the person of faith—that is, Christian cognitive claims are more personal than those made in scientific discourse.

> God, for the orthodox, speaks to us and takes us into his divine self. This grace transforms us as objects who are subjectivities. Theology, must, therefore, be conducted in terms of a moral pilgrimage of self-transformation in the light of knowledge graciously induced and shared among the faithful. God is not an object about which we can formulate theories that can be tested for their adequacy against a rather flimsy and remarkably self-authenticating data base. God is a person who transcends, creates, and inspires, and who imposes the divine personality on the process of gaining knowledge.[50]

Despite this personal emphasis, the positions of Puddefoot and Gillett do not actually depart from Murphy on this personal dimension. But, we ask: is the personal dimension isolated or in relationship to God? Can we reduce all objective knowledge of God to personal or subjective testimony? Not if one is a realist. Murphy would respond that data subject to theological reflection includes the impact of knowledge of God on the life of virtue lived by the person of faith. The holist position incorporates both the objectively real and our subjective awareness of the real.

This interaction between Murphy and her critics tells us something important, namely, theologians cannot do justice to their craft without responding personally to the impact of our personal God on our thinking. "Faith involves not just a way of looking at the world, but also a personal trust in God," writes van Huyssteen. "An ultimate faith commitment to God is, in this respect, more like trust in a friend or a spouse than like belief in a scientific theory."[51] If it is a canon among scientists to treat the objective physical world in an impersonal manner, the theologian must respond at some point to the personal dimension of God's gracious activity. Whether this affects the epistemology of CR is another question to be posed.

Should theology adopt a postmodern methodology? We offer a conditional *yes.* Holistic postmodernism presents itself as a healthy option, because it seeks to overcome the split between subject and object and retains both in a single epistemology. Deconstrutionist postmodernsim is less attractive. Even though deconstructionism aptly points out the distortions in human subjectivity due to social location, its demand that objectivity bow entirely out of the picture of reality seems excessive. Neither science nor theology could adapt to the deconstructionist epistemology.

6. Can Critical Realism build a bridge between scientific and theological methodology?

It appears at first that critical realism in science could be matched by a corresponding critical realism in theology. Like the scientist who is unable to see the Higgs boson—or an electron, for that matter—the theologian does not see God. Like the scientist who measures the effects left by the alleged Higgs boson from its decay particles using the detector in the LHC, and the illuminative power of the math at work in the conceptual model of the Higgs boson, the theologian measures the effects of God's grace in human experience and the illuminative power of the symbolic language that refers to what is unseen. Both the scientist and the theologian rely upon a faith or trust in their assumptions; and they both look forward to fertile new insights that these assumptions might yield.

New Testament scholar N.T. Wright embraces CR:

> I propose a form of *critical realism*. This is a way of describing the process of knowing that acknowledges the *reality of the thing known, as something other than the knower* (hence 'realism'), while fully acknowledging that the only access we have to this reality lies along the spiraling path of *appropriate dialogue or conversation between the knower and the thing known* (hence critical).[52]

Why? Does critical realism offer something of intrinsic value to the theologian? Or, is the value of critical realism only to build a bridge between theology and science?

"This critical realist quest for the best explanation provides ... a common ground on which the dialogue between science and theology can take place," writes Polkinghorne.[53] Knut-Willy Saether follows suit. "Both science and theology aim to say something about the same world, and this brings science and theology into dialogue. This means critical realism in science is not directly transferred to theology, but finds its parallel in theological critical realism."[54] In sum, critical realism has intrinsic value for the theologian. It also has value for the dialogue between theology and science.

Peacocke presses the case for theologians to share the same methodological scheme with the same subjectivism employed by scientific critical realists:

> I urge that a critical realism is also the most appropriate and adequate philosophy concerning religious language and theological propositions. Critical realism in theology would maintain that theological concepts and models should be regarded as partial and inadequate, but necessary and, indeed, the only ways of referring to the reality that is named as 'God' and to God's relation with humanity.[55]

With a bit more detail, Van Huyssteen describes the theological task in terms of a "weak" version of critical realism: "A qualified or weak form of critical realism, therefore, does not at all offer a strong defense of theism, but attempts to deal with and make more plausible the cognitive claims of religious language and theological reflection."[56]

Kees van Kooten Niekerk offers still more detail. He affirms the continuity of CR in both science and theology, but its use must take into account three distinctive features of theology. First, whereas the reality referred to in science is physical and generally accepted as real, theology posits the reality of God whose existence is widely disputed. All other factors being equal, theological claims will lack the plausibility of scientific claims. Second, whereas scientists can test their theoretical claims through experiment, theologians cannot access God through experiment. Third, whereas scientific descriptions claim to be impersonal and value neutral, theological claims are personal and value laden. "Whereas scientific statements are … statements of fact, theological statements include valuations. Therefore, it is prima facie not obvious that critical realism as a theory of factual or theoretical knowledge can be transferred from science to theology."[57] However, these differences should not be exaggerated. Despite the differences, if we focus on the cognitive claims of theology—the existence of God is a factual claim, for example—then theological inquiry presumes a critical realism that is quite similar to that presupposed in the sciences. "Science and theology in principle are justified in claiming that their statements and propositions tell something about a mind-independent reality."[58]

Niekerk offers three reasons for transferring realism from science to theology: (1) like science, theology makes cognitive claims; (2) science seeks to explain sense-experience in terms of nature just as theology seeks to explain religious experience in terms of God; and (3) both science and theology employ metaphors and models as approximate—not literal—descriptions of an external reality.[59]

What we see here are proposals for theologians to copy what scientists do, to adopt the critical realist stance when pursuing theological research and theological speculation. Might we refer to this as the parallelist proposal? What scientists do for the physical realm, the theologians do for the spiritual realm. The scientific reference is the physical world, whereas the theological reference is God and God's relation to the physical world. Parallel and consonant, but not connected.

But, we ask: Are these parallel employments of critical realism sufficient? Are they intellectually satisfying? If we keep the domains of science and theology parallel though separate, then the parallel methods may be interesting, to be sure. But, not much more. Can we bend parallel uses of CR so that they intersect?

For more than the three plus decades Robert John Russell has sought to encourage two way traffic over the "methodological bridge that critical realism provides between theology and science."[60] He does not actually rely on the critical approach to reality referred to in each of the two disciplines. Rather, he asks first for a creative mutual interaction (CMI) between the disciplines to point us toward the one reality with which both fields need to attend. Instead of a parallel copying of science's critical realism by theology, Russell proposes that the two fields together produce a synthetic approach to realism which takes critical self-understanding into account.

Critical realism is the name we ascribe to a recommended epistemology. CMI may embrace the brand of realism we have been working with here; but then it looks for a variety of pathways to take theology toward science and science toward theology. CMI is not dependent on CR.

If our goal is CMI, then parallelism between science and theology in CR is not enough. The dramatic significance of critical realism would rise if it becomes a factor in the creative mutual interaction or, more precisely, the incorporation of the scientific engagement with reality into the theological engagement with reality. If in CMI a fertile research program leads to expanded or deepened knowledge of God—the God who is real—then CMI will have provided an added methodological blessing.

Gregersen locates the drama at the transdisciplinary level.

> The dialogue [between science and theology] is a meta-discipline that forms theories about the place of science inside a broader framework of meanings and values, including religion. In other words, the science-theology dialogue is, in my view, about the *transdisciplinary interpretation* of the methods and results of science inside the broader perspective of different views of life, in our case that of the Christian tradition.[61]

Gregersen, in contrast to Murphy who combines coherence with reference, is a strict coherentist.

> The coherence emphasis is about how to make sense of the different aspects of the world rather than how to give a causal explanation of specific processes of reality. The primary role of theology is therefore, in my view, to form proposals about *interrelations of meanings*, seen from the specific resources of Christian tradition, rather than offering *causal explanations* in competition with non-theological [scientific] alternatives.[62]

We ask: is coherence enough? Not for the critical realist, either in science or theology. We would like to see a progressive or fertile research program—perhaps even a research program derived from CMI—that leads somewhere, that leads to a fruitful new insight. A holistic model that includes subject and object not only *within* theology but also in *creative interaction* with science might provide the epistemology that gives us the confidence that we are dealing with reality and not merely our subjective imaginations.

Explanatory adequacy

Before concluding, we would like to tease out one more nuance regarding theological methodology. Because we cannot measure the accuracy of our claims against the object of our claims, we must appeal to an indirect measure. We have already mentioned fertility, i.e., the ability of a conceptual model to generate progressive research. The model of the Higgs Boson proved to be fertile. The mathematics sowed the seed, and the LHC brought that seed to blossom.

We would now like to bump this fertility criterion up to the next level by appeal to the criterion of *explanatory adequacy*. Does a robust Christian vision provide a deeper or more comprehensive picture of reality? Does it explain more? Does the disputed God hypothesis at the center of the theological claim illuminate more reality than alternative claims?

Relative explanatory adequacy relies upon four sub-criteria: applicability, comprehensiveness, logic, and coherence.[63] By *applicable*, we mean that there are some instances of actual contemporary experience or even scientific knowledge to which theology applies. Although empirical research could provide the experiential component we are talking about, more than likely it will be a personal or existential experience to which the theological explanation provides the most realistic re-description. By *comprehensive*, we mean there are no significant experienced actualities that in principle are not interpretable and explainable according to the theological scheme. Everything in reality is oriented around the God of grace; and new experiences are fittingly integrated into this comprehensive conceptual model. By *logical* we intend for theology to be consistent, to avoid self-contradiction. If we confront mystery or paradox, then mystery and paradox become components in the explanation and not contradictions. By *coherence* we refer to an intra-systematic coordination that requires various principles to complement one another. To cohere, each principle needs to presuppose its sister principles so that the theological scheme looks like an interlocking web of interpretive commitments. Coherence is no substitute for correspondence, to be sure; but it strengthens without absolutizing the comprehensive conceptual scheme.

In sum, theology can share with contemporary physics a presupposed critical realist epistemology, a method that creates a conceptual model to explain what cannot be seen, either physical particles or God. Still, some models are relatively better than others, even in theology. The criterion of explanatory adequacy provides an indirect measure for discerning the more illuminating theological models.

Conclusion

The search for the Higgs boson is one of the exciting scientific adventures of our era. Like pirates passionately searching for buried treasure, particle physicists followed a map, a mathematical map presented by their conceptual model. It just may be that the treasure has been found, right where the map said it would be. Just as a pirate awaits the evaluation of the assayer, we are now awaiting confirmation of the LHC data.

Similarly, theologians work with conceptual models that point to realities unseen. God is unseen. Yet, God is real. Or, at least theologians must work with a critical realist set of assumptions that presuppose God's reality. The value of such a theological model will be determined by its fertility, its ability to progressively open up new vistas and expand horizons of our understanding.

Now, if we place the physicist and the theologian in the same room and ask for creative mutual interaction, what might happen? Even more fertility? More treasures found?

Endnotes

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8 Ibid., 43.

9 Ian G. Barbour, *Religion in an Age of Science*, Gifford Lectures 1989–1991 Volume 1 (New York: Harper, 1990), 43. See *New World Encyclopedia*, "Critical Realism," available at http://www.newworldencyclopedia.org/entry/Critical_realism

10 CERN is the center for particle physics research with the world's largest hadron collider (LHC). A hadron is any subatomic particle that interacts by the strongest of the four fundamental forces of nature, strong, electromagnetic, weak and gravitational. It is a composite particle composed of quarks. The laboratory is also called CERN. The Collider has a number of detectors, The ATLAS and CMS for example. CERN has ~4,000 employees, and serves as the particle physics laboratory to ~600 universities from 113 nationalities.

11 M. Delia Negra, P. Jenni and T.S. Virdee, "Journey in the Search for the Higgs Boson: The ATLAS and CMS Experiments at the Large Hadron Collider," *Science* 338:6114 (December 21, 2012): 1560–1568.

12 The authors wish to express appreciation to David M. Kline, a PhD student in statistics at the Ohio State University for his helpful discussion on significance levels. The discovery was based on a test of significance against finding the Higgs particle by providing a probability, P-value, at some level. A significance level of 0.05 was chosen. This value provides a 95% confidence level (CL), an accepted standard, thereby signifying a discovery. The discovery has been published for 2 different collaborations at CERN, for the ATLAS collaboration in *Physics Letter B* 716:1 (September 17, 2012): 1–29, and the CMS collaboration can be found on pages 30–61. Each group met the CL independently. Also, the CDF and D0 collabrations at the Fermilab report data which is most significant in the mass range between 120 and 135 GeV (giga-electron volts). Their results are in press at the time of this article, but can be found at http://arxiv.org/abs/1207.6436.

13 Gordon Kane, *The Particle Garden: Our Universe as Understood by Particle Physicists* (Addison –Wesley, 1995), 53–70. Kane provides a full nontechnical description of the AQ4 "Standard Model" which he refers to as the "Standard Theory" in Chapter 4. Chapter 8 presents a discussion on the Higgs boson. This book is an accessible, thought-provoking and friendly account of the particle physics journey. In principle, the standard model provides a complete description of all known natural forces and interactions in the physical universe by the elementary particles given in its table except for gravity. It gives in detail how the leptons—the electron is a lepton—and quarks fit with the gauge bosons and the Higgs boson.

14 In teaching chemistry and physics classes 1964–2005, Carl Peterson described how scientists approach their work and especially how he tackled research problems. The original reference and guide for his scientific thinking and development was Farrington Daniels and Robert A. Alberty, *Physical Chemistry*, 2nd ed. (New York: John Wiley, 1961), 4, 5. Also, in a memorandum dated February 22, 1988 to the Biological and Physical Sciences Faculty at Columbus State Community College, Peterson outlined scientific thinking and guidelines to formulating theories from his perspective. A natural sciences course was being developed at the time by the college, and he was asked for his input on its development. And Douglas C. Giancoli, *Physics*, 4th ed. (Englewood Cliffs, NJ: Prentice Hall, 1995), 1–7, describes the activity and practice of science.

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28 Peacocke, *Theology for a Scientific Age*, 12.
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