# The Engineering Knowledge Research Program

Professor Terry Bristol

Institute for Science, Engineering and Public Policy

Affiliated with Portland State University

bristol@isepp.org

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**Abstract**

The engineering knowledge research program is part of the larger effort to articulate a philosophy of engineering and an engineering worldview. Engineering knowledge requires a more comprehensive conceptual framework than scientific knowledge. Engineering is not 'merely' applied science. Kuhn and Popper established the limits of scientific knowledge. In parallel, the embrace of complementarity and uncertainty in the new physics undermined the scientific concept of observer-independent knowledge.

The paradigm shift from the scientific framework to the broader participant engineering framework entails a problem shift. The detached scientific spectator seeks the 'facts' of 'objective' reality – out there. The participant, embodied in reality, seeks 'methods', about how to work in the world. The engineering knowledge research program is recursively enabling. Advances in engineering knowledge are involved in the unfolding of the nature of reality. Newly understood, quantum uncertainty entails that the participant is a natural inquirer. 'Practical reason' is concerned with 'how we should live'– the defining question of morality. The engineering knowledge research program is selective seeking 'important truths', 'important knowledge', 'important methods' that manifest value, and serve the engineering agenda of 'the construction of the good.'

The importance of engineering knowledge research program is clear in the new STEM curriculum where educators have been challenged to rethink the relation between science and engineering. A 2015 higher education initiative to integrate engineering colleges into liberal arts and sciences colleges has stalled due to the confusion and conflict between the engineering and scientific representations of knowledge.

**Introduction**

At end of World War II a new awareness arose of the importance of science and engineering in modern society. The enormous post-war government funding for science and engineering required a clarification of their relationship. President Truman asked Vannevar Bush, an engineer and inventor, who had headed the U.S. Office of Scientific Research and Development during World War II. To his credit Bush responded that he didn't really understand the relationship.(1) However, in the immediate political and economic context Bush proposed that science should be understood as research and engineering as application. Engineering was subsequently characterized as applied science. Not everyone agreed.

Forty-five years later Dr. Walter Vincenti, Stanford professor of aeronautical engineering, presented a challenge in a book with the provocative title, *What Engineers Know and How They Know It* (1993).(2) Vincenti boldly questions what had become the institutional relationship between the dominant scientific-based theory of knowledge and an insurgent engineering theory of knowledge. Vincenti offers: "Modern engineers are seen as taking over their knowledge from scientists and, by some occasionally dramatic but probably intellectually uninteresting process, using this knowledge to fashion material artifacts. From this point of view, studying the epistemology of science should automatically subsume the knowledge content of engineering." He then adds: "Engineers know from experience that this view is untrue." (2) Vincenti illustrates his point by noting that scientific knowledge, albeit a useful tool, doesn't tell you how to build an airplane.

The engineering knowledge research program aims to articulate the engineering theory of knowledge. The overall hypothesis is that the engineering theory of knowledge is more general than the scientific theory of knowledge. The engineering representation of inquiry and knowledge formally subsumes and supersedes the limited validity and applicability of the scientific theory of knowledge. This project is part of a broader research program aiming to develop a superseding philosophy of engineering and a corresponding overall engineering view of reality. I have attempted to separate the epistemological (viz. theories of knowledge) questions from the ontological questions (viz. the composition of the world). Such a separation can of course only be a matter of emphasis. A follow-up essay will focus on the ontology of the engineering worldview.

**The Relevance**

The early reviewers of this essay suggested that it would be valuable to mention the immediate relevance and practical importance of developing an engineering theory of knowledge.

The new STEM curriculum (viz. Science, Technology, Engineering and Math) is the most prominent educational initiative tacitly calling for an upgrade in our theory of knowledge. Two decades ago the emphasis in high school technical subjects was exclusively on science and math. Science Fairs were about demonstrating scientific phenomena. Later the fairs became science and technology fairs. Robotics fairs more fully captured interest in technology and engineering design. In the new curriculum teaching engineering presents a new problem. Teaching faculties in high schools as well as in higher education have themselves been educated within the limited scientific theory of knowledge. Bush's division was presupposed. 'Science' is research and 'engineering' is 'merely' the application of scientific knowledge. If the engineering knowledge framework is the more general then current faculties are ill prepared to teach the E portion of the STEM curriculum.[3]

There is also a rising consciousness within the engineering community itself. To cite one initiative, in 2015 MIT engineering professor Louis Bucciarelli under the sponsorship of MIT and the National Academy of Engineering[4][5] organized a conference to reconsider the place of engineering in the higher education curriculum. As a result of Bush's defining separation of the scientific and engineering enterprises, engineering had entered higher education as semi-autonomous colleges of engineering. The education appropriate to engineers was tacitly thought distinct from the more comprehensive education of the liberal arts and sciences students. Given the increasing awareness of the crucial role of engineering in the development of modern civilization there is a broad consensus of the need to expand engineering education. Bucciarelli's initiative proposes to broaden engineering education by bringing colleges of engineering into the more comprehensive intellectual context of liberal arts and sciences.

At the 2015 conference, aside from the expected resistance of engineering deans to a possible loss of their relative autonomy, there was an unexpected intellectual pushback. The engineering educators pointed out that the liberal arts and sciences representation of knowledge was 'detached' from the practical reality of the engineering enterprise. The detached, scientific spectator theory of knowledge conceives inquiry as seeking 'knowledge for knowledge sake'. Indeed if the deterministic scientific worldview is correct engineering knowledge has no real value. A quip from Nobel physicist Steven Weinberg captures the objectionable sentiment: 'Isn't it quaint that the engineers believe that they can change the course of events and alter the structure of reality since we physicists know whatever happens is fully determined by the universal scientific laws governing everything from the beginning of the universe.'(6)

The takeaway from the intellectual pushback at the conference was that the need for educational reform was reciprocal. Just as current engineering education needs to broaden to include aspects of the liberal arts and sciences tradition, the liberal arts and sciences tradition needs to broaden to include aspects of the 'real world' practical enterprise.

The problem can be illustrated by a personal anecdote. In the early 2000s in a meeting with Ron Adams, then dean of engineering at Oregon State University, he and I discussed these issues, in particular with reference to Bucciarelli's earlier books, *Philosophy of Engineering* (7) and *Designing Engineers* (8). I suggested to Adams, who was largely sympathetic to the overall issues, that he might include a philosophy course in the engineering curriculum. After some discussion the takeaway remark was Adams's question: "Which of my engineering professors do you think I should fire in order to hire a philosopher to teach my students about existentialism?"

What struck me immediately was that current academic philosophers, and indeed current humanities and human sciences faculty were ill prepared to address the overlapping issues. The dominant intellectual traditions in the colleges of arts and sciences were inadequate to 'educate' the engineering tradition. Just dumping a lot of humanities and human sciences courses on the engineering student without some sort of 'new more general philosophical integration' would be pointless.

At the symposium there was a clear and explicit recognition that there was a fundamental philosophical division, a discontinuity, between the engineering tradition and the arts and sciences tradition.(5) To put it simply the arts and sciences were as divorced from a knowledge and appreciation of the engineering tradition as the modern engineering tradition had become divorced from the liberal arts and sciences tradition. If Bucciarelli's proposal, that we integrate the colleges of engineering and the colleges of arts and sciences, was to succeed there needed to be a consensus across all disciplines that the intellectual adjustment needed was reciprocal. The arts and sciences had adopted a 'pure' self-conception that entailed that the 'practical' progressive agenda of engineering was inherently separate. The practical engineering agenda was in a crucial sense irrelevant to their conception of their agenda of acquiring 'pure knowledge.' As Vincenti had argued the notion of 'engineering knowledge' just didn't translate into the traditional liberal arts and sciences theory of knowledge.

Per hypothesis, what is needed to accomplish the reintegration of the liberal arts and sciences and the engineering traditions is a new superseding understanding extending beyond and subsuming both the 'pure research' and 'mere application' images. One missing element of the proposed new understanding is an engineering theory of knowledge. We need to understand the nature of engineering knowledge and how is it acquired?

**A Brief Outline**

The engineering theory of knowledge is more general than the scientific theory of knowledge. Just as the spherical earth understanding subsumes and supersedes the limited flat earth understanding, the engineering theory of knowledge both subsumes and supersedes the inherently limited scientific theory of knowledge. The more general understanding subsumes the successes of the prior understanding, explaining them in a new way. The expanded, superseding framework understands the 'same' phenomena in a conceptually discontinuous new way. In the spherical earth framework, realizing that human observer-actors are very small on a very large sphere, the supposed successes of the earlier flat earth framework are understood as having been 'reasonable' even though formally false when consider as a complete representation of the whole picture. By analogy with the flat-to-spherical transition, the transition to the more general engineering knowledge framework requires a paradigm shift, a qualitative conceptual expansion. The new more comprehensive engineering paradigm cannot be derived from the earlier less comprehensive scientific paradigm. One impediment to the transition is that validity of the engineering paradigm as superseding (viz. by analogy again with the spherical earth theory) can only be understood by evaluating it from the perspective of the new framework.

Although the leap forward cannot be reasoned logically from within the prior limited paradigm, the paradigm shift is not totally blind. There have been increasingly bold, hopeful, piecemeal explorations portending a direction. In recent history there were three lines of reasoning critical of the scientific theory of knowledge. These have provided clues pointing to an engineering theory of knowledge. A brief background account of each of these will lay important groundwork.

**FIRST – the critique from the history and philosophy of science**

My academic career began in the philosophy of science where the dominant Positivist model suggested that scientific inquiry was, or at least should be, systematic, should be logico-mathematical. This Positivist position 'stood to reason' if one accepted that the universe was governed by universal mechanical laws. Thomas Kuhn, Paul Feyerabend, Imre Lakatos and Karl Popper rebelled developing a critique of the Positivist representation. In his careful investigation of the historical record, Kuhn found that advances in knowledge were not logico-mathematically systematic as the Positivist model predicted. Major advances in particular involved logico-mathematical discontinuities. In his famous book, *The Structure of Scientific Revolutions* (1962), Kuhn proposed that advances involved conceptually revolutionary paradigm shifts. Following Kuhn and the work of many others it became clear that it was not possible to logically reason ones way from the earlier understanding to the new advanced revolutionary understanding. Even when there was considerable evidence against the old paradigm, the path to the new paradigm could not be logically reasoned. The path of progress wasn't logico-mathematical but involved adopting qualitatively new ways of understanding. The new, more comprehensive paradigms both subsumed and superseded the prior successes of the old paradigm – understanding them in a new way.

Popper, Feyerabend and Lakatos pointed out further inadequacies of the Positivist representations of scientific method and scientific knowledge. According to the falsifiability criteria no meaningful knowledge, by its very nature, could be 'objectively' true – valid for all time, everywhere. All experimental demonstrations must fail under some circumstance. Consequently, all scientific theories must be false in the sense of being incomplete (viz. non-comprehensive). The classical scientific notion that there could be One comprehensive scientific truth had to be discarded. Popper's most rigorous approach established that for every successful scientific theory there must be a formally complementary, conceptually discontinuous, successful scientific theory. The simplest illustration is the conceptual complementarity of particle and wave theories in physics. Particles are local in space and time and waves are non-local. Particles and waves are inter-defined such that a particle is by definition a non-wave, and a wave is by definition a non-particle. There is not and cannot be any conceptual common denominator from which both types of phenomena could be logico-mathematically derived.

As in the case of particle physics and wave physics, per hypothesis, all observations, by their very nature, and all corresponding scientific theories, involve a conceptual, qualitative bias.

There can be many successful mechanical scientific theories but they all involve some form of conceptual idealization. Taken individually, neither particle physics nor wave physics can be, by their very nature, conceptually comprehensive. Consequently all meaningful scientific theories are special cases with limited validity. Popper's falsification argument entails that any comprehensive understanding of reality cannot be scientific. In order to properly understand the successes of the many successful scientific theories – in a new way – what is called for is a more comprehensive understanding of reality. Any such qualifying worldview must be able to formally subsume and supersede the scientific worldview and the successes of all possible scientific theories. The more general worldview must be conceptually revolutionary, understanding reality in a new way, suggesting the need for a paradigm shift.

**SECOND – the crisis of the new physics**

Modern science from Galileo through Newton had been founded on the scientific hypothesis that all phenomena in the universe are governed by one universal order. The scientific hypothesis can be reasoned quite simply from the defining characteristic of 'genuine' scientific knowledge – that it must be repeatable. Galileo's experiment dropping the balls from the Tower of Pisa in the 16th century can be repeated here and now. Scientific knowledge must be demonstrably repeatable over changes in time and location. The scientific hypothesis is that the order governing all phenomena must be demonstrably repeatable over changes in time and location. The order must be time-space invariant, the same from the beginning to the end of time, everywhere.

The new 20th century physics – quantum theory and relativity – empirically demonstrated the inadequacy of the scientific hypothesis. The new physics demonstrated that there were conceptually distinct types of phenomena and correspondingly logico-mathematically discontinuous types of laws governing them. What was particularly surprising was that these phenomena and these laws were formally complementary – inter-defined opposites. The so-called wave-particle duality demonstrated that there are at least two logico-mathematically discontinuous types of mechanical laws (viz. classical and statistical) governing at least these two incommensurable, opposite types of phenomena. Since particle phenomena are characteristic of the Newtonian framework and waves are characteristic of the Maxwellian framework, these two entire conceptual frameworks are actually complementary.[(12)]

In a paradoxical manner the empirical demonstrations of the new physics formally undermined the scientific hypothesis that there is just one conceptually complete and logico-mathematically consistent order governing all phenomena. In addition the notion of independent (neutral) observations of 'objective' reality was undermined. The phenomena and the order that an inquirer discovers depends to some irreducible extent on where, when and by what experimental methodology the investigation was made.

Einstein put the dilemma succinctly: "[Traditionally] Physics is an attempt conceptually to grasp reality as it is thought independently of [how] its being observed. In this sense one speaks of 'physical reality.' In pre-quantum physics there was no doubt as to how this was to be understood. In Newton's theory reality was determined by a material point [completely localized] in space and time; in Maxwell's theory, by the field [completely distributed] in space and time. In quantum mechanics it is not so easily seen."[13] Richard Feynman made a blunt assessment: "I think I can safely say that nobody understands quantum mechanics."[14]

If scientific reality cannot be understood, cannot even be referred to unambiguously, then how are we to proceed? Quantum cosmologist Lee Smolin reflected that when his generation entered physics in the 1960s they were excited, hoping to resolve the question of the nature of quantum reality, a question, they felt, had been left in confusion by the founders. He recently told a group of incoming graduate students: "It is now 2009 and it has become rather Kafkaesque that we have made no progress whatsoever."[15]

Reality in the new physics can no longer be properly represented as objective, independent of being observed, independent of when, where and how it is observed and investigated. The inquirer can no longer be made sense of as a detached spectator seeking the universal order governing a deterministic objective reality – 'out there'. In the new physics the inquirer is a participant embodied in reality facing an essentially existential situation: having distinct observational opportunities, necessarily choosing, and yet with nothing that determines or unambiguously directs that choice. Consequentially, the necessary choice can't be made sense of within any universal scientific, objectivist framework. In reflections on the new physics the inquirer's choice is commonly represented as 'arbitrary'. On the other hand, the inquirer's choice is not simply un-determined – is not entirely random, and not entirely free. All choice is to some irreducible extent constrained. The choice is better represented as under-determined, partially dependent on historical time and location and on the inquirer's ability and resources.

In quantum theory the inquirer's choice is often symbolized in terms of the 'collapse of the wave function'. The wave function represents the constrained, local field of potential choices for the inquirer. In the broader perspective, since the inquirer is a part of reality with each choice the field of potential choices and the inquirer transform. The potential field plus inquirer emerges into one historical future rather than another. The new present 'contains' the historical fact of the prior choice that was made. As reality evolves the history of the choices must be a cumulative aspect of the structure of reality. Past and present choices alter future opportunities.

Among the hardcore defenders of the scientific worldview, being unable to make sense of 'choice', a favorite intellectual dodge is the curious notion of the multiverse. They propose that the embarrassing concept of choice can be eliminated, if, somehow, all choices occur and all potential historical futures actualize deterministically in observationally distinct and independent universes. In any case, whatever universe one finds oneself in, it contains and is the result of the cumulative history of unique (viz. scientifically 'arbitrary') choices. In either case there is a conflict with the expectation of the scientific hypothesis that the universe (any universe) should be timeless and non-historical.

Heisenberg's Insight was that complementarity entails an irreducible uncertainty for any one way of observing or understanding reality.[(16)] De Broglie pointed out that the uncertainty results because every observation contain both an order and an irreducible element of the opposite complementary disorder.[(17)] If you try to understand reality in one way, in terms of one order, scientifically, there will always be an irreducible uncertainty, an irreducible incompleteness, an irreducible lack of conceptual completeness.

In addition Heisenberg noted that it wasn't just the particle and wave phenomena that are complementary but also the corresponding experimental setups that demonstrate each type of phenomena. Taking this one step further the sequence of actions leading to the construction of the different experimental setups is also complementary. Action in the world is not strictly determined. All action involves a bias, an irreducible, scientifically 'arbitrary' choice.

There are four key takeaways from the new physics that point toward an engineering theory of knowledge. First, there is a move away from unconditional objectivity. All scientific knowledge (viz. all empirically demonstrable regularity) has boundary conditions. A more comprehensive, superseding understanding of scientific knowledge must involve an irreducible reference to the 'who, what, when, where and how' of the observational support.

Second, the quantum choice that symbolically (and paradoxically) collapses the wave function requires the observer to be a part of reality, an embodied participant.

Third, the quantum choice also entails that the evolution of the universe is logico-mathematically and mechanically discontinuous, selectively unique and historically cumulative.

Fourth, complementarity is an essential aspect of reality resulting in Heisenberg's irreducible uncertainty for any one way of measuring or trying to understand reality. Inquiry can no longer be fully represented as a convergence toward one universal objective understanding of reality.

There is a strong mutual support between the themes that arose from the new philosophy of science and the themes that arose from the new physics. Both point, per hypothesis, toward a more general participant theory of knowledge that subsumes and supersedes the scientific theory of knowledge. All this supports the proposed the paradigm shift from the spectator to the participant representation of inquiry and knowledge.

**Parallel Hypothesis**

In what I have come to refer to as the Parallel Hypothesis there is a parallel between ideas of how inquiry proceeds and ideas of the nature of reality. For instance, the Positivist representation of inquiry by a logico-mathematical scientific method parallels the scientific hypothesis that all phenomena are governed by One universal time-space invariant mechanical order.(12) If either the logico-mathematical method or the mechanical reality were correct the other would follow naturally, would – 'stand to reason'. One should expect a similar parallel between the proposed revolutionary process of learning, proposed by Kuhn, Popper, Lakatos, Feyerabend et al. and the nature of reality as historically unfolding.(9)(10)(11) It would – 'stand to reason'.

**THIRD – the challenge from the engineering community**

The third 20th century stimulus of the new engineering theory of knowledge, mentioned above, arose within the engineering community. Their concerns seem to have been completely independent of the critical developments in the new philosophy of science and the new physics. Vincenti's challenge was born of a frustration over the general failure of the technical community to appreciate that engineering knowledge was different and that its study was not correctly subsumed under the study of scientific knowledge.

Vincenti also finds the scientific ontology to be inadequate. If engineering creations are not ‘merely’ the result of ‘applied science’ then there can be no complete scientific account of the current engineering world of airplanes, cell phones and so forth. The scientific worldview simply can’t account how the current structures and functions of engineering reality came to be and can provide only limited insights as to how they work.

More recently in the 21st century engineering community there has been a growing self-critical examination of the place of the engineer in society.[18] In his recent book, *The Essential Engineer: Why Science Alone Will Not Solve Our Global Problems* (2010), Duke University engineer Henry Petroski offers a bold expansion of Vincenti’s themes. According to Petroski, what we have been casually referring to as scientific inquiry can only properly understood as a subroutine within the more comprehensive engineering knowledge research, development and deployment enterprise. Petroski argues that the engineering worldview subsumes and supersedes the scientific worldview. Meaningful inquiry and knowledge can only be understood in the framework of the practical engineering enterprise. Inquiry doesn’t even make sense in the deterministic scientific worldview, has no value, and therefore isn’t meaningful.

Petroski’s engineering way of understanding doesn’t reject or replace the scientific view it subsumes and supersedes. For Petroski it isn’t a matter of science versus engineering. There aren’t scientists and engineers. They are all engineers. I recall my own moment of revelation. I had casually imagined that I was a scientist seeking the universal laws governing objective reality. Then I realized that, since there were no universal laws, I couldn’t have been doing what I imagined myself to have been doing. The new physics made clear that what many scientists thought they were doing, on closer examination, never really made sense. If the universe including the scientists were governed by a fully deterministic order, inquiry doesn’t make sense. And more practically if all actions are fully determined the scientist is not ‘actually’ in a position to freely design and run experiments to check his results. To put it succinctly the scientific worldview is not self-referentially coherent.

In Petroski's representation of the engineering process, we learn by doing. The process is always somewhat blind and uncertain, necessarily experimental and exploratory. At least in part we try to do things and learn from our failures. When acquired engineering knowledge is recursively enabling opening qualitatively new opportunities for further experimental explorations.

That's the background.

## The Paradigm Shift is a Problem Shift

One unexpected lesson of Kuhn's rigorous investigation of the real history of advances in knowledge was that even when the inadequacies of an otherwise successful theory might be clear to both its proponents and critics a new better superseding theory doesn't just automatically appear. Major advances are conceptually revolutionary and cannot be reasoned from within the current theory even with considerable demonstrated counter-evidence. Proponents and critics may be frustratingly 'stuck' for long periods unable to abandon the current successful, but clearly inadequate, theory. Even when the advanced framework arises the transition to the new way of understanding is difficult and gradual.

I have tried to represent each of the three 20$^{th}$-century lines of critical reasoning as being 'stuck'. Popper, Lakatos, Feyerabend and Kuhn detailed the inadequacies of the Positivist representations of the history and philosophy of science. Bohr, Heisenberg, Planck and de Broglie argued that the empirical demonstrations of quantum theory established the inherent inadequacies of the classical scientific way of understanding reality. Vincenti's challenge details the fundamental inability of the scientific theory of knowledge to make sense of engineering knowledge. At best each of these lineages provided only clues to the paradigm change needed to bring forth the new better understanding of reality.

American pragmatist John Dewey offered a simple characterization of what I will defend as the proper paradigm shift.[19] Dewey distinguished two representations of inquiry and knowledge, the spectator and the participant. The spectator representation corresponds to the classical scientific portrayal. The spectator is a detached inquirer seeking the universal order (laws) governing objective reality – 'out there'. The spectator's initial uncertainty (ignorance) declines as knowledge advances. Successful inquiry is represented as a convergence toward a complete and consistent scientific knowledge of objective reality. The spectator's criterion of genuine scientific knowledge is that it is 'repeatable over changes in time and location'. Consequently the overall order governing all phenomena is time-space invariant. A crucial feature of the spectator representation of inquiry is that the actions of the inquirer must not alter the course of events or the structure of reality. If the inquirer interferes with the natural course of events while investigating then the opportunity would be lost to converge to an objective (viz. observer-independent) reality. He would be unable to separate the effects of his interference from the natural course from effects.

On the other hand, in the participant representation of inquiry the inquirer is embodied in reality, a natural component of reality. The participant representation accepts the inevitable, natural influence of the inquirer within reality. The participant representation precludes any complete and consistent convergence to an independent, 'objective' reality. When the participant learns reality learns. An advance in participant knowledge (per hypothesis, engineering knowledge) develops the nature of reality. The participant's knowledge is not *about* reality as if like a detached scientific description. Participant knowledge is a development *within* reality, an irreducible aspect of reality. Reality for the participant is naturally historical, changing with the successful inquiry.

Per hypothesis, quantum theory requires a participant framework. The embodied participant observer's choice selects one unique historical path among the potentials and cumulatively develops the ongoing potential of the observer-plus-universe. The scientifically 'arbitrary' quality of the quantum choice cannot possibly, by its very nature, be made sense of conceptually within any possible mechanical scientific theory. The new physics, the new philosophy of science and the engineering perspective all point toward a participant framework. The paradigm shift opens (viz. or re-opens) a new type of questioning. William James, in his 1906-07 Lowell Lectures commenting on what appears to be an earlier attempt to articulate this same paradigm shift, referred to 'pragmatism as a new name for an old way of thinking.'(20)

The engineering knowledge research program is a work in progress. What I offer here is an interim report from the field highlighting what appear to the author to be important characteristics worthy of further investigation. I have yet to find one best way to organize my results and the results of others. I have chosen an experimental approach organizing findings as responses to a series of questions: What? – the nature of participant engineering knowledge; Who? – the nature of the participant inquirer; How? the method of learning; When/Where? – the history and cumulative structure of the embodied engineering knowledge; and finally, Why? – the fundamental motivation and the shift to the value context. Each response to each question category constitutes a slightly different perspective on the core project of articulating an engineering theory of knowledge. These approaches inevitably overlap, hopefully in ways that are mutually illuminating and reinforcing.

**What is participant (engineering) knowledge?**

Perhaps the single most important insight about the paradigm shift from a spectator to a participant representation of inquiry is that the transition entails a problem shift. For the spectator the problem of inquiry is to understand 'how the universe [out there] works'. Einstein states the classical view plainly: "Physics is an attempt conceptually to grasp reality as it is thought independently of its being observed. In this sense one speaks of 'physical reality.'"[13] For the participant, embodied in reality, the problem of inquiry is something like 'how to work in the world'.

Answers to the spectator's scientific questions are 'facts' (viz. repeatables), about what is regular and fixed, seeking the time-space invariant order governing phenomena. In contrast, answers to the participant's 'how to work in the world' questions are 'methods'. The 'methods' are about how to do things. Participant inquiry subsumes the idealized representation of scientific inquiry as a subroutine in the broader participant agenda. Gathering relatively stable facts is preliminary to doing something with them.

In the participant's superseding framework scientific facts are newly understood. All facts and their associated theories are falsifiable, valid only within certain boundary conditions. Whether the electron is a Newtonian-like particle or a Maxwellian-like wave is undecidable as an objective question in the scientific framework. In the participant understanding these scientific 'facts' are always changing in the dynamic, mechanically discontinuous unfolding of the nature of reality. Learning about the world scientifically – the facts – involves adopting the idealizing presupposing that the nature of reality is in a steady state.

As a thought experiment it is helpful to try to distinguish two stages of participant learning. In the first stage the participant inquirer can learn *about* how the world around him currently works. To learn, in this initial idealized sense, about how the world works is to learn about the current system, understood in a new way, as composed of dynamic embodied methods. However, the participant himself is a dynamic embodied method in the world of dynamic embodied methods. The participant inquirer is a methodological process *within* a world of methodological processes. In the second idealized stage of learning the participant learns how to do something new. When he learns a new method he learns something meaningful insofar as it is an advance in the context of the defining question of participant inquiry – how to work in the world. The new knowledge (viz. method) alters the participant's relationships *within* reality. Per hypothesis participant engineering learning involves the formation of novel progressive synergistic relationships. Instead of the spectator's idealized detached learning *about* a fixed reality (viz. out there), the inquirer is newly understood as a participant, and better characterized as learning *with* – and *within* reality. The initial picture of an ontology of dynamic embodied methods suggests a process reality, reminiscent of Whitehead's Process Philosophy.(21)

In the broader philosophy of engineering research program I had expected to be able to keep questions concerning engineering knowledge (viz. epistemology) separate from questions concerning the composition of engineering reality (viz. ontology). With the recognition that the participant, as well as what the participant learns, must be part of the composition of reality, these two lines of research, the epistemic and the ontic merge. Despite the merger, in this essay I will continue to focus on the epistemological, on the nature and characteristics of engineering knowledge. Nonetheless one comment that applies to both the epistemology and ontology will be helpful. Because the participant framework naturally embraces quantum complementarity reference to the embodied engineering knowledge cannot be understood as any sort of 'scientific', time-space invariant objective description. The dynamic methods embodied in a process reality cannot be understood as interrelated in only one 'objective' right way at any one preferred moment or location. The interrelationships of the embodied processes are not like an eternal Newtonian clockwork. Plausibly, the interrelationships of the methodological ways of being are better understood along the lines of the new post-scientific ecological paradigm[22]. One might imagine the biosphere developing through an inherently symbiotic, cumulative, emergent 'learning with' process.

Acquiring new engineering knowledge is like adding to a tool-kit of potential actions, potential ways of choosing how to work in the world, potential ways for the world to work. However, the history of advances in engineering knowledge cannot be understood as a simple additions or increases of one conceptual type. Engineering knowledge will reflect complementarity. There should always be both opposite and alternative methods, ways of doing things. There should always be different ways of observing/looking at, describing and explaining the 'same' thing where there is no 'objective' common denominator. This is exemplified by the complementary particle and wave ways of understanding the electron. Each of the disciplines as well as the overall architectonic of engineering knowledge should incorporate and reflect complementarity. The complementarity of engineering knowledge allows us to understand why all inquiry isn't just physics.

Another reason advances in engineering knowledge cannot be understood as an increase of one conceptual type is that there is a qualitative (viz. revolutionary) expansion of types of capabilities, types of potentials. Improvements in engineering methods, thought of as inventions, are unpredictable, unexpected and surprising by their very nature. Later inventions are conceptually different, not logico-mathematical derivations from earlier inventions. How a new invention works cannot be understood in terms of earlier inventions (viz. or scientific facts). And the prior ways of understanding how the earlier invention worked are to some irreducible extent understood in the new way in the more advanced understanding (viz. how flat earth surveying tools work is understood in a new way in the spherical earth framework.)

A better characterization of how these new methodological inventions come into reality and how reality transforms as a result is at the leading edge of research in the philosophy of engineering.

**Who is the participant inquirer?**

The participant is natural inquirer embodied in reality. The uncertainty of the new physics is embraced in the participant engineering framework, but newly understood. For the participant inquirer the uncertainty means he is constantly facing a choice. In quantum theory the participant's choice is referred to as 'arbitrary', reflecting that it cannot be made sense of within the classical scientific framework. In the superseding participant framework the choice is not detached or abstract but involves real action in the world. Heisenberg's insight was that not only are the wave and particle phenomena complementary, but that the experimental setups that demonstrate these phenomena are, in some irreducible aspect, also complementary. Taking this one step further the sequence of actions needed to create the alternative experimental setups must also be, in some irreducible aspect, complementary. All choice-action in the world involves a bias because the choice is between qualitatively distinct complementary opposites. Popper's falsification requirement supports this conclusion since for any successful experimental setup there must be an equally successful complementary experimental setup that can demonstrate an opposite type of phenomena.

Real inquiry cannot be made sense of as a mechanical 'happening' as the Positivists proposed. Because of the qualitative bias in the choice the participant's actions are better understood as 'doings'. Uncertainty entails that the doings can never be understood as completely mechanical. Participant inquiry is a 'learning by doing', always somewhat experimental and exploratory, a literal action *within, as part of,* reality. Apparently, successful learning by doing must involve some sort of teleological component.

The participant's future, although constrained, is inherently under-determined. The outcome of an intended action, a doing, a method, can never be fully assured. All apparent repetitions have an irreducible uniqueness in time and place. Every experimental trial has an irreducible exploratory aspect in time. Since the choice actualizes only one of the possible futures, the participant's cumulative present always has an irreducibly unique historical aspect.

Newly understood in the participant framework the uncertainty is, per hypothesis, an expression of the necessary freedom of choice in all action. The participant is of necessity constantly choosing how to work in the world. The participant is a natural inquirer. The uncertainty constitutes a problem, a tacit question – how should I act? The participant's future, although constrained, is always inherently under-determined. Every action is concomitantly a doing and a questioning. The Continental Existentialists characterized the participant as instantiated in reality with (1) the ability to act, and (2) with the natural necessity to choose. However, the existential participant lacks a script. There is nothing to tell him how he should act. Although there are local constrains there is nothing that fully determines how he acts. How he chooses to act is always under-determined. The Continental Existentialists often found this realization to be anxiety provoking. The modern engineer understands this openness as representing the opportunity for truly creative problem solving.[23]

Participants are practical value-opportunity actualizers. What I have referred to as Carnot's Epiphany[24] is that participants are engineers in a world of engineering. Alternatively expressed participants are doers in a world of doings, choosers in a world of choosing, learners in a world of learning.

**How does the participant-engineer learn?**

It is crucial to recognize that the engineering knowledge research program is self-reflexive as an inquiry into the developing nature of inquiry. The question of the nature of inquiry is not an independent (viz. spectator) question about a fixed reality. Inquiry cannot be properly understood, or developed, from outside of inquiry itself. American Pragmatist Josiah Royce proposed what I refer to as Royce's Criterion of Self-Referential Coherence.[12] Royce pointed out that whatever theory about the nature of reality that you propose, that you have learned, must be able to account for itself and its having been learned. The understanding of reality must itself be a part of reality. Royce begins by arguing that whatever theory you propose must be able to account for the existence of problems. He referred to this as 'the problem of problems'.[25] Two fundamental types of problems concerned Royce: the problem of ignorance (viz. knowledge) and the problem of evil (viz. value). A fully deterministic scientific worldview is unable to make sense of, let alone explain our 'beginning' ignorance. Similarly the ideological representation of science as 'pure' research has no way to make sense of the value of knowledge. The 'knowledge for knowledge sake' theme expresses that the scientific research program has no reason to expect (or accept) that scientific knowledge has any value. In the scientific worldview there is no meaningful inquiry and there is no meaningful knowledge.

By contrast, the engineering worldview and the engineering theory of knowledge outlined in this essay pass the test of Royce's Criterion of Self-Referential Coherence. As I have argued the participant framework entails that the new superseding way of understanding the scientifically enigmatic quantum uncertainty entails that the participant is a natural inquirer. The uncertainty and the choice don't decline with advances in engineering knowledge. The uncertainty simply transforms and develops. New types of questions emerge with each advance. The participant's ignorance is natural, necessary and ongoing.

Another entailment of Royce's reasoning is that inquiry, learning and problem solving processes in general must be irreducible aspects of the methodological nature of reality. The epistemic enterprise is ontic. As a limited characterization the inquirer might be thought of as learning *about* a world that is learning *about* the inquirer. However real, meaningful advances in engineering knowledge involve learning *with* others in a way that develops reality. Reality is concomitantly self-referentially learning about itself, unfolding the nature of reality. Royce's reality is an emergent learning system, an emergent engineering knowledge research program. Royce's reality is a dynamic autodidactic, exploratory bootstrapping enterprise.

The individual can only learn by recognizing the limits of his own current way of understanding. This occurs through the appreciation of other complementary successful ways of understanding. When the recognition is reciprocal 'enlightened learning' can occur generating a sort of synergistic advance of methodologies.

Another novel characteristic that differentiates engineering inquiry and knowledge from (the supposed) scientific inquiry and knowledge develops is that when we learn we also learn concomitantly how to learn. With an advance in knowledge there is an advance in methods (of inquiry). It's not just that advances open new vistas for questioning and exploration. With advances in engineering knowledge we learn how to question better, how to inquire in a qualitatively better way. We become better inquirers (viz. more intelligent) – concerning how, when, where and about what to inquire in order to discover increasingly valuable knowledge. Engineering knowledge is about methods and consequently is recursively self-enabling. Unlike the Positivist's supposedly one universal timeless scientific method, in the engineering knowledge research program the method of inquiry itself develops and improves. If engineering knowledge and methods of inquiry (intelligence) develop over time the implication is that reality's learning system becomes increasingly intelligent about how it explores, more intelligent about what questions to ask, more intelligent about how to ask them, when and where.

In his book, *What Technology Wants* (2010), Kevin Kelly, founder of *Wired Magazine*, emphasizes this meta-reflexive theme that when we learn we also concomitantly learn how to learn – better. Kelly argues that, "Not only is the aggregate process of evolution evolving, but it is evolving more ability to evolve, or greater evolvability… The evolution of evolution is change squared."(26)

**When/Where is the embodied inquirer and engineering knowledge?**

In the scientific worldview observational evidence was considered to be objective and, as such, neutral between different competing theories. However, both philosophy of science and the complementarity of quantum theory establish that both observation and ways of understanding are not objectively invariant. All observation is theory-laden. Since embodied engineering knowledge is emergent what you can observe and how you can act in the world depend on when, where and how you choose to observe (relate). How an actor-observer chooses is constrained by his own embodied potential as well as local embodied opportunities. The emergence of engineering knowledge can only be fully understood in its historical context.

University of Victoria biologist Robert G.B. Reid proposes a superseding participant engineering view of biological evolution in his book, *Biological Emergences: evolution by natural experiment* (2007).(27) Reid understands organisms as natural inquirers, as creative agents characteristically exploring and experimenting with new ways of working in the world, with new ways of interrelating. Reid understands biological systems to be seeking engineering knowledge, naturally seeking new better ways of working in the world, seeking win-win symbiotic interrelationships that increase their capacity as well as the capacity of the system to perform work.

Reid provides a superseding understanding of Darwinian ‘random mutation’. In model Darwinian it is presupposed that when organisms are reproducing they are attempting to produce identical copies of themselves. Variation can only arise ‘accidentally’ from ‘copying errors’. Darwin’s introduction of ‘random errors’ is curious if not enigmatic. The expectation of the scientific worldview, of Newton’s clockwork reality, is for a conserved mechanical Steady State system that does not ‘evolve’. By contrast in Reid’s engineering model the expectation is that biological systems naturally generate experimental, exploratory variations. As uncertain natural inquirers, innately experimenting and exploring, organisms instinctively (deliberately?) generate variation. In the participant engineering knowledge process variation is expected and an integrated ecological-like diversity of embodied knowledge processes makes sense.

In Darwinian evolution populations are supposed to be adapting to, a sort of convergence, their local fixed environment. By contrast Reid observes that as populations advance they achieve increasing ‘adapt-ability’, a qualitative broadening capacity to live and work in more diverse environments. Life isn't adapting *to*, it is constructively emerging *from*. What is emerging in the overall system is an expansive ability to do things. What is emerging is engineering knowledge.

Ecologist Robert Ulanowicz in his book, *A Third Window: Natural Life beyond Newton and Darwin* (2009), argues in concert with the themes of this essay for a post-scientific understanding of the emergence of the biosphere.(22) Ecologist Eric Schneider and Dorion Sagan, in their book, *Into the Cool: Energy Flow, Thermodynamics and Life*, represent the biosphere as an engine (viz. an agent able to perform engineering work). The engine of the biosphere evolves in a way that is analogous to the historical evolution of steam engines through successive (critically recursive) design improvements.(28) Through these improvements the biosphere increases its capacity to perform work (both qualitatively and quantitatively).

In support of the participant engineering way of understanding reality, master engineer George Bugliarello argued that modern engineers should be taught that what they are doing is a natural extension of biological evolution.[29] The tacit implication is that biological evolution, the evolution of the biosphere leading to human civilization is the result of an unfolding, experimental exploratory engineering enterprise. Organisms and ecological systems are themselves naturally inquiring, naturally developing embodied methodologies.

There has been a parallel paradigm shift in economics from classical scientific equilibrium economics to a participant engineering understanding referred to as New Growth Economics. In scientific equilibrium economics supply and demand always work toward a Steady State equilibrium. Since engineering inventions (viz. tools and rules) are unpredictable, they could not be the result of mechanical supply-demand activity. The appearance of engineering knowledge had to be the result of external, 'exogenous', influences. In 1990, Stanford economist Paul Romer published an article entitled "Endogenous Technological Change"[31] where he argued for a new post-scientific understanding of economic systems. Romer argued that economic systems are engineering inquirers, naturally seeking qualitatively new, better ways of doing things. Economic systems are naturally, by their very nature, engaged in the seeking and generating engineering knowledge. By analogy with Kuhn's reconsideration of the history of science, Romer newly understands the history of the civilization. Real, meaningful economics is a historically emergent engineering knowledge research and development enterprise. For Romer economic engineering enterprise is recursively enabling and self-reflexively accelerating. New Growth Economics supports Reid's biological emergence theme that engineering knowledge advances increase and broaden the capacity to perform engineering work.

**Why does the participant inquire?**

The second most striking feature of the paradigm shift from a scientific spectator theory of knowledge to a superseding participant engineering theory of knowledge is the reintroduction of value. Scientific inquiry is concern with achieving an objective description and explanation of how the causal mechanical world works. Passive predictions are supposed to confirm but are of no practical value. The scientific theory of knowledge is notoriously value-free. Reasoned from within the scientific research program there is no intrinsic value to scientific knowledge. We are often told that scientists are surprised that others find scientific knowledge of practical value since the aim of scientific research has no expectation of benefit. Indeed, since scientific reality is presupposed to be fully deterministic there is no way for this 'detached' acquisition of scientific knowledge itself to be of any real, meaningful practical benefit. As Nobel physicist Stephen Weinberg expressed it: "Isn't it quaint that the engineers imagine that they can change the course of events and restructure aspects of reality, since we physicists know that everything, including the actions of engineering are fully determined by the universal scientific laws."(32) When asked why they seek scientific knowledge the proponents suggest that the pursuit is 'pure' unfettered by practical concerns; 'knowledge for the sake of knowledge'.

To understand the engineering knowledge research program, it is crucial to realize that it is not seeking all or just any methods. The engineering knowledge research and development enterprise seeks to discover and development methods that recursively promote the emergence of the nature of reality. The engineering enterprise is not seeking all possible ways of working in the world, all possible ways of doing things in reality. Engineering knowledge research seeks the desirable, the valuable, ways of doing things. It is not to strong a statement to suggest that the primary concern of the engineering knowledge research program is to learn what is valuable and in the process manifest it.

Can't get an ought from an is. Same as saying that you can't get from the scientific to the engineering framework concern with value, with understanding and manifest how we should live. Not fixed or pre-conceivable.  by any logico-mathematical reasoning from within the context of the scientific 'is' world. On the other hand the paradigm shift to the engineering knowledge framework allows us to subsume and supersede the supposed scientific 'is' world of facts understanding it in a new way. We can get, so to speak, the 'is' world from within the broader 'ought' world. The ought world is the very different from the supposed scientific 'is' world. Inquiry makes no sense in the 'is' world. In the ought world, what we ought to do is the aim of inquiry, the aim of the engineering knowledge research program, always open-ended and emergent.

For the participant inquirer the question 'why do you seek engineering knowledge' is a little strange since participants, embodied in reality, are natural inquirers. The question is similar to asking why you choose (to act) when choosing is a natural necessity. The meaningful question is 'why do you make the choices that you do'. The participant is making real, practical choices that manifest different historical sequences. In his *Critique of Practical Reason* (1788, 2004) Immanuel Kant pointed out that the choices of practical reason concern how we should live.[(33)] Kant then notes that the question 'how should we live' is the defining question of morality. Accordingly the natural defining question of practical reason is about morality. The engineering knowledge research, development and deployment program is properly understood as naturally concerned with the unfolding of a moral reality. Nobel laureate Herbert Simon argues similarly that engineering problem solving is the attempt to move from a current state of affairs to a more desirable future state of affairs.[(34)]

Founding American Pragmatist Charles Sanders Peirce argued that all meaningful questions arise in the participant's real world practical context. Consequently, all meaningful knowledge, all answers to real meaningful questions, must, by their very nature, have practical benefit, real value, for the participant's natural engineering enterprise.[(35)] University of London philosopher Nickolas Maxwell argues that meaningful inquiry naturally seeks "important truths" concerned with 'how we should live'.[(36)] In concert with Peirce, Maxwell is critical of the misrepresentation (and to some extent the practice) of inquiry in academia as 'scientific' in the sense of being detached from the practical and value-free. Maxwell emphasizes that the aim of inquiry is not to discover the 'one' specific and timeless utopian way of working in the world. For Maxwell the aim of research and development should be toward greater wisdom (viz. as to how we should live), to better understand what is of value and how to manifest it in the world. American Pragmatist John Dewey characterized the embodied engineering knowledge research program, of which this essay is, self-referentially, an element, as engaged in 'the construction of the good'.[(37)]

Recognition of the natural value of engineering knowledge and the engineering inquiry enterprise suggest that reality is an embodied recursively unfolding moral intelligence. The nature of the engineering knowledge and the nature of reality emerge qualitatively. The path of the emergence (viz. like inventions) is unpredictable. The specific nature of the goal and the path isn't pre-conceivable, isn't teleological. As Lao Tzu expressed it in the ancient *Tao Te Chung*, "The path that can be spoken [pre-conceived] is not the [real] eternal path."(38) Concerning the path forward, some will tell you that whenever in doubt (viz. which is always) always turn to the right. Another will tell you whenever in doubt always turn to the left. Each of these specifiable iterations closes in on itself and self-destructs. Per hypothesis, the path forward must always involve *a learning with* involving an irreducible aspect of both complements.

At a 2013 meeting of the American Physical Society John Heilbron, Berkeley professor of history of science, reexamined the broader worldview of quantum physicist Niels Bohr: "The primary payoff of his engagement with quantum physics for his wider philosophy was the discovery that multiple truths come… in complementary pairs."(39) Citing newly available correspondence with his fiancée, Margrethe Norlund, Bohr discusses the different truths expressed in sermons, great works of literature, and science. These all differ in kind, but all are important. Bohr wrote: "It's something I feel very strongly about, I can almost call it my religion, that I think that everything that is of value is true."

In 1893, Pragmatist Charles Sanders Peirce, citing numerous ancient wisdom precedents, noted that progressive philosophies and theologies from the earliest times seemed to have a common vision of the nature of our developing reality. Peirce's famous speculative essay was entitled "Evolutionary Love".(40)

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