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Grounding Aeronautical Engineering Education in Engineering Thermodynamics

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Grounding Aeronautical Engineering Education in Engineering Thermodynamics

The aim of this paper is to present the case for a foundational course on The History of the Philosophy of Engineering Thermodynamics in Aeronautical Engineering Education. I am indebted to reviewers for encouraging a refocusing of the theme. The current submission should be understood as still a very rough work in progress to be followed by the more complete argument and syllabus in the final submission.

Preview of the Argument

Aeronautical engineering is founded on aerodynamics. The basis of aerodynamics, properly understood, is Dynamics. The formal understanding of Dynamics arose in the 17th century articulated by Gottfried Leibniz in the contrast between Statics and Dynamics. It was Leibniz who first introduced the term Dynamics into thinking about how the world works. However, as economist Kenneth Arrow observed, Dynamics traces back to early Greek geometry and engineering. Arrow suggested that Dynamics "is like an underground river" in the history coming to the surface now and then, here and there. Princeton historian Gillispie characterized what Leibniz presented as a shift from Statics to Dynamics as a transition in the 17th and 18th century from concern with 'the science of mechanics to the science of machines (engines)'. Experimental studies of both the winds, aerodynamics, and water, hydrodynamics contributed to the new understanding of Dynamics. At the end of the 18th and beginning of the 19th centuries in the contributions of Lazare and Sadi Carnot we see Dynamics as the foundation of thermodynamics, of engineering thermodynamics.

Thermodynamics constitutes the most general framework of both the sciences and engineering. Oxford's Peter Atkins, in his book, *The Second Law*, pointed out that there are two histories of thermodynamics. "Carnot traveled toward thermodynamics from the engine. Boltzmann traveled to thermodynamics from the atom." Then Atkins surprises, claiming that "Thermodynamics still has both aspects." Engineering thermodynamics is more general, subsuming and superseding the Clausius, Boltzmann, Gibbs mechanical formulations. Engineering thermodynamics is conceptually more sophisticated, able to make sense of the engineers' constrained freedom, as well as system evolution.

Manchester's Donald Cardwell recognized that the correct history and formulation of thermodynamics had to do with engines. Cardwell notes that "Almost traditionally, it seems, accounts of the development of the concepts of work and energy have tended to describe them within the classical framework of Newtonian mechanics." Then he moves to emphasize, "I would like to suggest that this may be to take too narrow a view of the case."

Cardwell realized that the historical concern of thermodynamics was about machines and engines, emphasizing the pioneering contributions of Sadi Carnot on steam engines and John Smeaton on waterwheels. Cardwell came to realize that the history of thermodynamics was inseparable from the history of machines and engines reaching back to Archimedes and earlier.

In 1888, Scottish engineer William Rankine observed, "The improvers of the mechanical arts were neglected by biographers and historians, from a mistaken prejudice against practice, as being inferior in dignity to contemplation; and even in the case of men such as Archytas [an ancient Greek philosopher] and Archimedes, who combined practical skill with scientific knowledge, the records of their labours that have reached our time give but vague and imperfect accounts of their mechanical inventions, which are treated as matters of trifling importance in comparison with their philosophical speculations. The same prejudice, prevailing with increased strength during the middle ages, and aided by the prevalence of the belief in sorcery, rendered the records of the progress of practical mechanics, until the end of the fifteenth century, almost a blank. Those remarks apply, with peculiar force, to the history of those machines called PRIME MOVERS." (The capitals are Rankine's)."[1]

Modern engineering thermodynamics provides the most general formulation and understanding of Dynamics. Aerodynamics is not a 'science', despite the convenience of differential equations for calculation. Differential equations are Static, presupposing time-reversibility. Dynamic processes, best described in engineering thermodynamics, include an irreducible irreversible component. This entails a cumulative, constructive engineering worldview that is more general and crucially different from the scientific worldview.

Moving from the scientific worldview to the more general, more conceptually comprehensive engineering worldview has been difficult because it involves a paradigm shift. Indeed, the paradigm shift is better represented as a meta-paradigm shift. Kuhnian paradigm

[1] W. J. M. Rankine, A Manual of the Steam Engine and Other Prime Movers, 12th ed., edited by W. J. Millar (Charles Griffin & Co., London,1888).

shifts were most often represented as occurring *within*, and thus preserving, the scientific framework. The shift from Statics to Dynamics is a meta-paradigm shift and is from the scientific framework and the scientific worldview to the engineering thermodynamic framework and the Dynamic engineering worldview.

To understand where all this leads in practice I offer the following learning objectives.

Learning Objectives

An aerodynamic engineering student having completed this course will be able to:

1. Recognize that historically aerodynamics has its proper conceptual foundation in Dynamics, the same foundation as for engineering thermodynamics.
2. Appreciate that the engineering thermodynamic worldview is self-referentially coherent and distinct from the scientific worldview, which is not.
3. Understand that engineering practice is not 'merely' applied science, and that engineering knowledge is an autonomous body of *enabling* knowledge.
4. Recognize the engineer as an irreducible, embodied component of reality, and is an active participant in the constructive evolution of the universe.
5. Realize that engineering practice is an autonomous enterprise with its own inherent value agenda, and that awareness of this "higher" agenda is essential for the engineer to be able to critically evaluate client requests.
6. Appreciate the value-added, the ROI, of this course, in achieving an understanding the thermodynamic structures and functions of reality, and the place and role of the engineer in the inherently evolving reality.

Introduction

Engineers have often been encouraged to think of engineering practice as 'merely' applied science. This misrepresentation of engineering practice and engineering knowledge has been largely due to the dominance of the scientific worldview and the scientific representation of knowledge.

Stanford aeronautical engineer, Walter Vincenti, in his seminal 1990 book, *What Engineers Know and How They Know It*, challenged the dominant scientific theory of knowledge. He noted: "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 counters: "Engineers know from experience that this view is untrue. [From an engineering perspective], technology appears, not as derivative from science, but as an autonomous body of knowledge. Aero planes are not designed by science, but by art – despite some pretense and humbug to the contrary. The creative, constructive knowledge of the engineer is the knowledge needed to implement that art."

Vincenti's core theme is that engineers and engineering educators need to present, explicitly, the engineering worldview with the corresponding understanding of engineering knowledge and engineering practice.[2] Duke engineer Henry Petroski, adopting the 'natural' engineering perspective, had an article in *The Washington Post* entitled, "If you want to change the world, don't ask a scientist, ask an engineer". Of the 100+ reader comments, all but a few were highly critical of Petroski's 'pretentious' assertion. But there is hope. I mentioned the negative comments to Petroski, who replied, "Yes, but it also generated a large number of invitations to speak." Nonetheless Petroski's experience highlights the need for engineers and engineering education to have a clear and distinct conception of the place and role of the engineer in reality.

Following Vincenti's theme Petroski argues that 'real' knowledge is and always has been engineering knowledge. Petroski argues that everything you thought of as 'science' can only be properly understood in terms of a more general, self-inclusive, participant engineering epistemology. This echoes a foundational argument of American Pragmatist C.S. Peirce, that all meaningful questions arise within a practical context.

A provocative entailment of Vincenti's thesis, that 'aero planes are not merely derivative from science', is that engineers are uniquely able to understand both the structures and functions of airplanes in a way that scientists cannot, and never will. If you want to understand both the structure and how airplanes work, don't ask a scientist, ask an engineer. The aeronautical engineer can understand the interrelationships of the parts and subsystems of an aircraft, not just

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[2] Vincenti was a student of Edwin Layton who opened many of these topics in the modern era through his many publications, including his famous book, *The Revolt of the Engineers: Social Responsibility and the American Engineering Profession.* Layton's efforts contributed to the STEM movement.

how they work as they do but their purpose, the *'why'* of the structures. The parts of the aircraft form an integrated whole and are mutually supportive in a way that is analogous to the parts and whole of an organism.

The engineer is also able to understand the purposes of innovations in the historical evolution of aeronautical technology. None of this is derivable from or understandable in terms of fundamental physics.

Vincenti extends his thesis toward a comprehensive engineering worldview. To illustrate the generality and fundamental nature of the engineering perspective, Vincenti points out that not only is the engineer in a position to understand the human generated structures and functions on the Earth, but if we were in the future to discover a planet, similar to the Earth, of similar size, with a similar atmospheric composition, and if there were flying organisms with exoskeletons, the aeronautical engineer could predict their size. This follows from an understanding of the power of their metabolic, thermodynamic engines and the principles of aerodynamic lift.

Vincenti's theme applies more generally, not just to flying organisms, but to the structures and functions of all living organisms, and of the overall planetary ecosystem. The structures and functions of these systems can be understood from the perspective of engineering knowledge in a way that science cannot, never will. If you want to understand the structures and functions of the living world, *again*, don't ask a scientist, ask an engineer. Furthermore, the engineer can understand the reasoning involved in the historical innovations in aeronautics. Technological structures and functions evolve, and each step is recursively enabling. Each design improvement increases the possibility space, and the opportunity to explore and to discover another design advance. Duke engineer, Adrian Bejan presents an account of the history of improving aircraft designs from an engineering thermodynamic perspective. Innovations are not deductions, but they are also not random. What Bejan focuses on is the *evolutionary reasoning*, the *why*, the purposes served by the innovations.

One of the practical benefits for the aeronautical engineer of being introduced to the philosophy of engineering thermodynamics and the engineering worldview is the value of the engineering perspective in understanding the structures and functions of the technological world, both how and *why* they might have evolved. This practical benefit is one of the 'returns on investment' as INCOSE thinks about the composition of the curriculum.

Master engineer George Bugliarello expands Vincenti's suggestion of an engineering worldview. Bugliarello argued that engineers should be taught that they are, and engineering practice is, a natural extension of evolution. Perhaps this seems obvious. But the implication is that biological evolution leading to the modern engineer, is, and always has been, a cumulative, recursively enabling engineering enterprise. Both the evolutionary history and the current technological structures and functions of reality are open to an engineering understanding, in a way that they are not open to scientific understanding. The paradigmatic presupposition of the scientific worldview that all processes are time reversible precludes any account of an innovative, recursively enabling evolution of the structures and functions of reality. The scientific framework is defined by the presuppositions of symmetry and conservation. What is perhaps not immediately obvious to those whose formal training was scientific is that the scientific worldview tells us essentially nothing directly about the actual structures and functions of reality.

From an engineering perspective evolution is a sequence of improvements in the technological design of the structures and functions of reality. The emerging design, including the shapes and structures of reality, and the purposes underlying their emergence are opaque to the scientific perspective. A common scientific attitude to such questions is to regard 'evolution' as a random, reversible process, on a path to nowhere.

Following Bugliarello's reasoning, technologies, from how we irrigate our fields to modern aircraft, embody engineering intelligence. Airplanes and airports and all the associated support systems embody the intelligence of the engineers who designed them. All these technological structures and functions are evolving, mutually supportive components of the overall system. Engineers themselves, as active components of reality, are both inquirers, and agents. Engineering actions at least seek intelligent solutions. Engineers themselves are highly evolved embodied intelligences. The parts of the human engineer form an intelligently integrated mutually supporting whole.

The Engineering Worldview

An important theme in the proposed course will be to understand the difference between the scientific worldview and the engineering worldview.

What always bothered me throughout my scientific education was the representation of scientific reality, of the scientific worldview, as thoroughly deterministic. This, of course, immediately conflicts with the engineer's sense of constrained freedom in engineering practice. It should be emphasized that if engineers have the ability, albeit limited, to alter the structures and functions of reality and the course of events, no account of engineers or engineering practice can be given from within the framework of a fully deterministic scientific worldview. There is no way to understand the value of engineering knowledge from within the scientific picture of reality.

Another way to emphasize the difference is that there is no way to make sense of either inquiry or inquirers within the scientific worldview. Knowledge has no value in a deterministic world. Without any account of inquiry, the scientific worldview cannot account for how the scientific worldview was supposedly learned. In other words, the scientific worldview can't account for or make sense of itself. In this sense, the scientific worldview is not self-referentially coherent. On the other hand, it can be argued that since engineers and engineering practice are embodied components of reality that the engineering worldview is, at least arguably, self-referentially coherent. Engineers are natural inquirers. Every engineering action is also a question. Finding an engineering solution presupposes a freedom in the process of discovery, in the process of learning.

Scientific knowledge is represented in terms of differential equations, as deterministic laws forming a picture of a fully deterministic reality, with no place for engineering inquiry and practice. Engineering knowledge, on the other hand, is enabling. Engineering knowledge is enabling suggesting that the engineer lives and works in a possibility space, in an evolving opportunity space.

One image of the engineering reality, based on the first few pages of his Sadi Carnot's famous essay, is what I refer to as Carnot's Epiphany: 'that we are engineers in a world of engineering, agents in a world of agency. In a more explicit engineering thermodynamic formulation we are metabolic engines in a world of metabolic engineering.

The Engineering Agenda and its Value Context

Following WWII, Vannevar Bush was tasked with characterizing science and engineering and their relationship. With some hesitation, Bush suggested that science should be seen as the leading-edge driver of inquiry and knowledge, while engineering should be viewed as “applied science”. In the 1980s Lehigh’s Stephen Goldman, in an overview study of engineering, expressed the then common notion that ‘engineers are given their values by their government or corporate clients’. In 2003, Dr. William Wulf, then President of the National Academy of Engineering, following a presentation in the Science, Technology and Society Lecture series in Oregon, was addressed by a questioner as follows: ‘I know what scientists do, they discover things. But what do engineers do?’ Wulf’s, unfortunate, but understandable, answer was: “Whatever they will pay us to do.”

There were earlier visionaries. In 1991, a group of leading engineers, including Walter Vincenti, put together a volume, published by the National Academy of Engineering, entitled, *Engineering as a social enterprise.* Their explicit theme was that engineering, unlike the supposedly value-neutral scientific enterprise, is fully embedded in the social enterprise. As Nobel economist Herb Simon expressed it, engineering is about real-world problem solving, and problem solving, by its very nature, is concerned with moving from a current state of affairs to a more desirable, more valuable, future state of affairs.

With the advent of the STEM (Science, Technology, Engineering and Math) initiative it has become common to see engineering as ‘problem solving’, indeed, quite often as solving social problems. ‘Science Fairs’ of the 20th century, where students were expected to exhibit some scientific principle, have been replaced by robotics competitions and celebration of novel engineering innovations. There has been a transition from engineering and technology being seen as ‘applied science/math’, to science and math being newly understood as ‘mere’ tools for engineering practice.

The takeaway is that the engineering enterprise does have an inherent autonomous agenda, separable from what any potential client might ask an engineer to do. It is only with this agenda, and the awareness of it by practicing engineers, that engineers can independently evaluate client requests. Without an autonomous agenda for all engineering there is no way to discuss the value context of engineering practice, to address the repeated disturbing questions such as the Holocaust engineering and the engineering of the atomic bomb. Without an autonomous engineering agenda these questions have no answers.

Nobel economist Herb Simon characterized engineering as problem solving, as attempting to move from a current state of affairs to a more desirable future state of affairs. The expression ‘more desirable’ is the value component. The issue isn’t about engineering ethics. It’s about the value of engineering practice. In discussing this issue with an engineering professor colleague we agreed that engineering was concerned with problem solving. We also agreed that the practicing engineer doesn’t really know what the problem is. My colleague told me that he teaches his students that they are ‘opportunity actualizes’, and more to the point ‘value manifesters’.

Here is where thermodynamics understood as engineering thermodynamics points the way, first toward the economics of engineering practice, then naturally toward questions of improving and maintaining social design. And it is only one, not too difficult step forward, to recognize that the engineering is naturally seated in a moral framework.[3]

Modern Philosophy of Engineering Dynamics

Beyond the historical perspective students should be introduced to modern philosophy of engineering and the engineering worldview. In my view American Pragmatism was a brilliant early attempt at a philosophy of engineering. John Dewey makes the crucial distinction between two representations of inquiry. The supposedly detached scientific Spectator is asking questions about a supposedly fixed, time-space invariant ‘objective reality’ – out there. The Participant inquirer is an embedded, embodied component of reality. The engineer, an active participant in the structures and functions of reality, is asking different types of questions than the scientist. The engineer is concerned with how to evolve the world from its current state to a more desirable future state. Dewey characterizes the engineer as a participant in the universal emergence of value, of ‘the Good’. This seems closely related to Timaeus’s theme that the universe, perhaps by its inherent nature as an engineering enterprise, always moves to the Good.

Practicing engineer Sam Florman explores and clarifies the nature of the engineer’s constrained but irreducible freedom in his book, *The Existential Pleasures of Engineering*. Louis Bucciarelli at MIT has been a leading proponent of the philosophy of engineering. In his book, *Designing Engineers*, he properly identifies design as the core agenda of engineering practice within the context of a socially defined enterprise. In *Philosophy of Engineering*, Bucciarelli, sees the concerns of philosophers as relevant to engineering thought and practice, in negotiating

[3] Worth repeating here is that neither the INCOSE Handbook nor the recent Mind Set essay make any reference to either thermodynamics or an autonomous engineering agenda.

tradeoffs, in diagnosing failure, in constructing adequate models and simulations, and in teaching.

The idea that engineering design is an autonomous[4] enterprise with its own inherent transcendent agenda is gradually gaining recognition. The prominent title on the cover of Harvard Business Review (2010) was "The Evolution of Design Thinking". Where Goldman had suggested that the design agendas for engineering practice came from government or corporate clients, the new perspective of the HBR essay pointed out that the problem of how to structure a corporation or a government is just as much an engineering design problem. The American Constitution is a design document outlining an experimental design agenda for how we should live together. Design question are universal: how should we design the irrigation of our fields, how should we design our houses, our neighborhoods, our cities? How should we design our economy? Common currency? Tariffs? And how should we design our government to preserve, maintain and develop our socio-economic system. Even personally, we all, in effect, are naturally faced with the questions about, how should I design my life? How much time for work, family, exercise and so forth. These were all questions raised in Plato's dialogue, *The Republic*. The HBR essay outlined a questioning heuristic, asking: Why are we doing this that way? What if we did it this other way? Yes, good thought. But how would you implement that?

Socrates suggested that the foundation of all questioning, of all inquiry, is: 'How should we live?' And this, I suggest, is best represented as the most general engineering design question.

Unless engineering has an autonomous agenda then it becomes a prostitute to all sorts of client requests. Only if engineering has an autonomous agenda can it challenge and modify client requests. Engineering has a systemic agenda to bring about a more desirable future. In the next section I will point out that such an autonomous engineering agenda was at the core of the Ancient Greek engineering worldview.

In the INCOSE Handbook, as well as in the new Mind Set document, I find no line of argument suggesting that engineering practice as a general enterprise in the universe has an being autonomous agenda. Arguably, per hypothesis, this is not unrelated to the fact that neither the Handbook nor the essay make any reference to thermodynamics.

[4] What is meant by 'autonomous' here is that it is separate and independent of any possible specific client request. Another way to express it is that engineering has an agenda that is more general, perhaps transcendent, than any possible specific client request.

Teaching Methods – Use of Case Studies

Among the possible methods of teaching the proposed course, I suggest the use of case studies. It should be possible to illustrate the character of engineering knowledge through the unique engineering character of the solutions.

A case study I have been developing is about the variable pitch prop in aeronautical design. It helps to illustrate the nature of engineering knowledge distinct from scientific. Scientific approach using variational calculus tends to look for the one 'least action' solution for the trajectory. The engineering knowledge presents the engineer with options, a constrained freedom. The engineer can vary the design of the coupling to 'optimize' for power at takeoff and landing and for efficiency while cruising.

One of the most creative aeronautical engineers on the last half century is Burt Rutan, who developed a number of innovative aircraft designs. Rutan also developed the re-entry strategy for SpaceShip One. The structure of the craft in ascent transitions to a shuttle-cock structure for re-entry. This re-entry solution constituted an entirely new innovative strategy.

A third case study might be about the discovery of the value of winglets on modern commercial aircraft. The aeronautical engineer should be able to understand both how they work, but moreover, *why* they are of value. Winglets also allow connection to Leonardo's 15^{th} century experimental investigations of all sorts of turbulence. Leonardo recognized that all transitions from one state of affairs to another involved an irreducible component of a turbulent counter-flow. Understanding the phenomenon of turbulence was not a concern to classical science.

Nobel Laureate Economist Kenneth Arrow referred to the themes of Dynamics as being like 'an underground river' in intellectual history, coming to the surface periodically.

The History of Philosophy of Engineering Thermodynamics

Main arguments in this essay serve to present engineering thermodynamic perspective along with its entailment and implications. But it is equally important to recognize that this perspective has a long history.

One serious lack in modern engineering education is the absence of any courses covering the history of the philosophy of engineering and the engineering worldview. At the beginnings of Western Philosophy, reality was seen as the result of cumulative engineering process. In Plato's dialogue, *Timaeus*, Timaeus is asked to provide an account of how the world came to be as it is. Timaeus argues that the emergence of the universe has followed the non-deterministic plan of the Archeteckton (Master Builder) or Demiurge (Public Worker). These expressions both suggest a Master Craftsman, a Master Engineer. Timaeus demurs on the specific path taken, claiming that he can only give a probable account. Clearly, there is freedom in the evolutionary path, but, he adds, emphatically, that one thing is for certain, that the emergence of the universe always moves to the Good, moves from each current state to a more desirable future state.

Plato's philosophy was inspired by Pythagoras who gave primary emphasis to recursively enabling geometric ratios and proportions, to evolving harmonic structures and functions. Plato's philosophy is *cosmogenic* addressing the constructive emergence of reality. Reality has an irreducible irreversible characteristic resulting in a cumulative history.

Emergent, *cosmogenic* frameworks are to be distinguished from modern scientific *cosmologic* frameworks. In the latter, the laws, expressed as differential equations, are time-space invariant, and all causal transitions are all time-reversible. According to the modern scientific worldview, these 'scientific laws' always have been and will be, always and everywhere. Grasping the difference with an evolving engineering cosmogony helps to understand why leading cosmologists, like Fred Hoyle, were dismayed by the evidence for a time-dependent history, leading to what Hoyle, pooh-poohed, as an origin of the universe with a 'Big Bang'. In the Clausius, Boltzmann, Gibbs mechanical interpretation of thermodynamics, the universal tendency of entropy to increase leaves open, the apparently unanswerable question of how to account for the initial low entropy at the beginning. If all processes are entropy increasing there is *no possible way* to account for a low entropy initial state.

Neither the cosmogenic, nor the cosmologic representation of reality seem to offer any plausible account of the origin of the universe, or an answer to the question of why there is anything rather than nothing.

The European Renaissance was a recovery of Ancient Greek geometry and engineering, to the Ancient approach to understanding the dynamically evolving structures and functions of reality.

The engineering approach and worldview re-emerged and significantly developed in the work of Galileo Galilei (1564-1642), Johannes Kepler (1571-1630), Isaac Newton (1643-1727), Christiaan Huygens (1629-1695), and Gottfried Leibniz (1646-1716). In his critique of the limitations of Rene Descartes, Leibniz proposed a transition from Statics, the science of mechanics, to Dynamics, the science of engines. Per hypothesis, this was proposing a transition from the scientific to a re-emergence of the engineering worldview. Worth emphasizing is that Leibniz's Dynamics involved a different 'engineering mechanics' and a different ontology, a world of engines. The new engineering mechanics became, through the work of Lazare and Sadi Carnot, engineering thermodynamics. These renaissance pioneers had been working on isoperimetric problems, the cycloidal behavior of pendulums and the proper understanding of phenomena such as vibrating strings. They all strongly favored the Ancient Greek geometric reasoning of ratios and proportions associated with Archimedes, Eudoxus and Euclid's *Elements Book V*. There was a common recognition of an essential duality in all processes and forms.[5]

Leibniz's meta-paradigm shift from Statics to Dynamics was newly appreciated fifty years later, by Daniel Bernoulli (1700-1782) leading to his novel research and development of hydrodynamics. Jean le Rond d'Alembert (1717-1783) engaged Leonard Euler (1707-1783) in a controversy over the proper understanding of harmonic oscillations in the vibrating string. The fundamental issue involved the correct definition of a function. Euler gave us the analytic function. D'Alembert more appreciative of the duality in the 'communication of motion' offered an engineering concept of function, as in the structure and *function* of the heart. D'Alembert's function embodied purpose and evolutionary propagation.

Euler, with his colleague Joseph-Louis Lagrange (1736 -1813) developed the tools of the analytic function. Lagrange famously declared in his Analytic Mechanics, that there were 'no drawings' in his mechanics. His new Variational Calculus completely excluded the Synthetic geometric approach tracing back to the early Greeks.

Pierre Louis Maupertuis (1698-1759) recovered Leibniz's framework based on a dualistic conception of an 'action'. Lazare (1753-1823) and Sadi (1796-1832) Carnot articulated a mature formulation of the concept of an action in their development of engineering thermodynamics.

One of the tacit suggestions arising with the appreciation of the historical split between the Analytic calculus and the Synthetic geometric dynamics is that there might be value for

[5] I address these question in more detail in my recent and forthcoming papers.

aeronautical engineering education to explore both the historical and practical difference between Fluid Mechanics, utilizing vector calculus and tensors and Fluid Dynamics of the communication of motion as a dualistic flow of ratios and proportions in engineering mechanisms.

Who Will Teach the Course and Where in the Curriculum?

These questions were raised by the reviewers. I have been struggling with these for over thirty years, marked by a discussion with a local Dean of Engineering. He asked what course should be dropped, and what faculty should be replaced to teach existentialism to engineering students. It was clear to me that such a course as in proposed here could not be taught by anyone without an engineering degree, excluding most contemporary philosophers. However, since most modern philosophy of engineering has been written and developed by engineers, such as Bucciarelli, Buglairello, Florman and many others, the answer is simply that engineering faculty with some accessible background are entirely capable of teaching such a course. Since the promotion of STEM similar adjusts have been made. As to finding room in the existing curriculum there are a number of historical examples innovative strategies, for instance, at Stanford, University of Washington and most dramatically at Olin College.

Dynamics and Thermodynamics

As developed in the earlier Preview section, thermodynamics provides the most general principles of both the sciences and engineering. Oxford's Peter Atkins pointed out that there are two histories of thermodynamics. Reviewing the historical literature is another way to illustrate the difference between the mechanical and engineering versions of thermodynamics.

Although Sadi Carnot's 1824 study of the steam engine in his essay on the motive power of fire is generally recognized as the formal beginning of thermodynamics. Over the following decades Rudolf Clausius reverted to a classical mechanical framework to reinterpret Carnot's original engineering thermodynamics. At first Clausius seems to endorse and laud Carnot's contribution. Clausius says, "Carnot proves that whenever work is produced by heat, a certain quantity of heat passes from a warm body to a cold one. This transmission Carnot regards as the change of heat corresponding to the work produced."

Clausius clearly recognizes Carnot's approach: "[Carnot] says expressly that no heat is lost in the process, and he [Carnot] adds, "This is a fact which has never been disputed; it is first assumed without investigation, and then confirmed by various calorimetric experiments. To deny it, would be to reject the entire theory of heat, of which it forms the principal foundation."

Clausius then completely rejects Carnot's 'principal foundation': "I am not, however, sure that the assertion, that in the production of work a loss of heat never occurs, is sufficiently established by experiment. Perhaps the contrary might be asserted with greater justice."[6]

It should not be difficult to imagine that Clausius and Carnot are speaking different languages, interpreting the heat engine from within different conceptual frameworks. Clausius's reinterpretation of Carnot's representation of engine interpreted 'heat', as produced from a fire, as the 'driving force' that necessarily declined as the fuel for the fire was used up as work is produced. Clausius found that in his approach he needed to introduce a new non-symmetric, non-conservative quantity to represent this decline in the capacity to perform work. This was the origin of the concept entropy and the so-called Second Law of thermodynamics. Since the 'principal foundation' in Carnot's model, is that 'heat', properly understood as *vis viva*, is conserved there is no Second Law in engineering thermodynamics. Recent scholarship has argued that Sadi's essay is largely an extension of his father's engineering thermodynamics, which has earlier roots in the meta-paradigm shift from Statics to Dynamics.

Lazare Carnot, in his mature 1803 essays, begins by noting that a 'well-known principle of engineering practice' that there is always a tradeoff between time/velocity and strength/power. Carnot emphasizes that this 'well-known principle' cannot be understood within any 'rational mechanics', within any modern mathematical physics. Archimedes expresses the principle in his account of the lever. Lazare suggests that all machines, the operation of all engines, can be understood in terms of the coupling mechanism of the lever. A crucial entailment of the 'well-known principle' is that engineers have *options* as to how they accomplish a task. They can, for instance, use pulleys to raise a weight taking more time, but accomplished with a smaller power source. Perhaps the most important point in Lazare Carnot's attempt to articulate an engineering worldview is that engineers always have options and thus a sort of constrained freedom. must necessarily make choices, in pursuit of optimum paths and structures.

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[6] Clausius, M.R. "On the Moving Force of Heat, and the Laws regarding the Nature of Heat itself which are deducible therefrom" Philosophical Magazine, Vol II, No. VIII, July 1851 Page 1-2

To establish systems engineering thermodynamics in aeronautical education, the history of engineering thermodynamics will be important. Leonardo da Vinci (1452-1519) is one historical contributor who should be of particular interest to aeronautical engineering, for any course in the history and philosophy of aerodynamics. His early studies in aerodynamics, particularly on the flight of birds, provided the basis of his brilliant and instructive attempts to design flying machines. His experimental investigations recognized the interrelations of hydrodynamics and aerodynamics phenomena. Leonardo's almost obsessive studies of turbulence were far ahead of his time. He came to recognize the irreducible component of an oppositional turbulence in all transformations. In his 'geometry done with motion' Leonardo understood all change in terms of an engineering thermodynamic conception of 'motion', as involving a composite duality. In his broad-ranging experimental engineering investigations he realized a deep structural unity underlying the phenomena associated with running, swimming, and flying. Unfortunately, most of Leonardo's engineering theory and worldview was hidden from his contemporaries and had little influence for a couple of centuries.

Bejan's Engineering Thermodynamics

Duke mechanical engineer Adrian Bejan has been struggling to make sense of engineering thermodynamics for over fifty years. I examined some of Bejan's work twenty years ago, saw that there was value, but I did not then appreciate the depth of what he had begun to articulate. I now believe that Bejan's mature work in understanding engineering thermodynamics will be of special value to aeronautical engineering education.

Bejan tells us that his core insight began to crystalize in 1996. His 1995 book, *Entropy Generalization Minimization*, was a prequel. The subtitle captured one of his core insights: *The Method of Thermodynamics Optimization of Finite-sized System and Finite-time Processes*. Bejan is attractively candid in admitting that he didn't fully grasp in the early days that he had 'a tiger by the tail'. His 2006 *American Scientist* article "Constructing Animal Locomotion from New Thermodynamics Theory" integrates and unifies the engineering dynamics of terrestrial locomotion, hydrodynamics of swimming and aerodynamics of flight.

Bejan's engineering thermodynamics dispenses with the concept of entropy, replacing it with a dynamic, constructive optimization process that naturally seeks to improve the structures and functions of reality. In Bejan's book, *Shape and Structure from Engineering to Nature,* it becomes clear that the scientific worldview, describing reality in terms of abstract scientific laws, relying on infinitesimal reasoning leading to the differential equations, told us nothing about the actual structures and functions of reality, or about the narrative of the irreversible dynamic geometric evolution of the structures and functions of reality. In his treatment of the evolution of aeronautic technology, and elsewhere on the evolution of technology in general, Bejan properly understands the place of engineering practice in the natural historical sequence of recursively enabling engineering practice.

Bejan recognizes, in concert with Carnot, that what engineers bring to the seemingly full table of scientific knowledge is *time*, and with it the grasp of the irreversible arrow of time as the path to better design, better system organization.

I explore Bejan's insight in more detail in my forthcoming essay, 'What Hath Bejan Wrought'. Bejan's contribution is a deep conceptual understanding of engineering thermodynamics. For me his core insights serve as a sort of rosette stone allowing one to translate and interrelate the major contributors to Engineering Dynamics, reaching back through the Carnots, to Leibniz, d'Alembert, Huygens and the Bernoullis to Aristotle, Archimedes and Eudoxus.