Chapter

# An Engineering Education of Holism: Einstein's Imperative

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## Abstract

In the aftermath of World War II, Einstein urged scientists to develop a substantively new thinking, lest we suffer a technology-enabled self-destruction. In this chapter, we will unfold the emerging scientific findings that serve as vectors, pointing to the same conclusion: the educational foundation that has brought about Industry 5.0 is causal to brain development that not only undermines our ability to address our emerging complex societal challenges, but biases us toward inhumane logic. We will outline a science of holism, the profoundly new thinking urged by Einstein. This science is rooted in nature's ontology of dynamic complexity. An engineering education reflecting this new thinking will be described along with the novel developmental capacities afforded by it. The chapter will end by considering questions that need to be resolved to manifest such a radical shift in engineering education.

**Keywords:** holism, holistic science, dynamic complexity, autopoiesis, emergence, health

## 1. Introduction: health intended; fragmentation produced

As we share these insights, we are aware that engineering education varies across cultures. Any insights are likely limited to the things we have in common. So, we begin with making clear our point of view (POV), which is derived from being immersed in engineering education in the United States since 1981. This education system is theoretically intended as the means to a profession that is dedicated to serving the well-being of society above all other considerations [1]. This purported purpose of engineering was not the core of our engineering education and subsequent teaching. The core was math and science, by which we are referring to the schools of western scientific thought, taught in English and traced to Thomas Aquinas, Francis Bacon, René Descartes, and Isaac Newton. Very briefly, as described by Capra and Luisi [2], Aquinas integrated scientific reason with faith, elevating what was scientific philosophy to God-given truth. The works of Bacon, Descartes and Newton served to produce an organized study of inanimate objects—changed only when acted on by force—and methods suitable for the study of such objects. Hidden in these paradigmatic shifts from philosophy to truth were assumptions and values that have functioned to shape our world as we know it today. Language is also relevant for its intimate coupling to our neurology [3]; like assumptions and values, its hidden structure unconsciously shapes our behavior [4, 5].

Our aspiration for engineering education, or all of education, is that of global health—societal and environmental, which we believe to be inextricably intertwined. However, at the moment of writing this, our country is reeling from what is apparently a systemic education gone wrong, writ large, and enabled by science and engineering. We 'westerners' imagine that our science and education support peaceful citizenship and democratic governance. Hundreds of years into this grand social experiment, the evidence suggests otherwise. Systemic patterns reveal our western education is most reliably producing fragmentation rather than health. In some ways, it is not surprising that a methodology of learning ("science") that is based on fragmenting the whole into its constituent parts does not produce health, the root of which is Old English hælþ "wholeness, a being whole, sound or well' [6]. As physicist David Bohm observed, "fragmentation is now very widespread, not only throughout society, but also in each individual; and this is leading to a kind of general confusion of the mind, which creates an endless series of problems and interferes with our clarity of perception so seriously as to prevent us from being able to solve most of them." (p. 1, [7]).

What we did not account for in our social experiment with 'western' scientific education, was the effect that education would have on our selves. In a recent book, Henrich [8] documents the research that shows that brains and behavior of western-educated adults differ in dramatic ways from their global peers. Specifically, these individuals, which Henrich describes as western-educated, industrialized, rich and democratic (WEIRD), have a default tendency to focus on parts within a visual field, whereas their non-WEIRD peers see the whole. Unsurprisingly, WEIRD individuals tend to view the world with the analytical thinking of the reductionist science that is core to western and engineering education. Reductionism and its methods assume a world of objects, held separate from and independent of the observer; its aim is to prove or disprove hypotheses about cause and effect. Reductionism is useful for manipulating the physical world for predictable outcomes but is not fit for the purpose of working with living beings. What this means for WEIRD people is a tendency to see human behavior as caused by traits of the individual whereas their non-WEIRD peers are more likely to reason that peoples' behavior is a reaction to the systemic conditions—a more holistic interpretation. WEIRD people tend to employ limited moral logics that rely on what are viewed as "autonomous" actions by individuals [9]. Non-WEIRD subjects draw on a multitude of moral logics that include autonomous action and presume ones' inseparability from communities. In short, western education conditions people to see the world in a fragmented, rather than holistic way.

Henrich's analysis of WEIRD subjects does not address the effects of the English language as the medium of WEIRD-ness. However, cognitive scientists recognize that language is neurologically embodied [5, 10]. For example, Lakoff and Johnson describe semantic frames in the English language which focus attention to what are considered salient features, causing unconscious entailments on peoples' behavior [4]. Might the language of engineering, deriving from military roots in the U.S., subconsciously condition behavior? Even the basic syntax of English-- *subject acts (on) object*--is noteworthy as a mental model of change. The English syntax is both linear and self-assertive. In contrast, the meaning of Chinese characters change with context; one must be attentive to context to understand meaning. Learning from written Chinese characters is essentially a practice in attentiveness to context. These brain practices required by the language may contribute to the results seen in a test for analytical v. holistic logic: Sixty percent of people from English speaking countries like the U.S., U.K. and Australia used analytical logic whereas sixty to ninety percent of people from China (depending on region) used holistic logic [11]. This result suggests that one's first language and its structure strongly condition one's attention, with Chinese students practicing more holistic logics. There is a dramatic increase of Chinese college students studying in English speaking countries (i.e., U.S., U.K., Canada and Australia), from the early 2000's on [12]. How do the logics of these Chinese students compare to their western-educated peers? This is an important question that the research literature in English does not yet seem to address.

Functional MRI studies of WEIRD subjects by Jack et al. [13, 14] point to patterns akin to what Henrich and others reported. They found that the neural networks active in reasoning about objects in the physical world have an antagonistic relationship between the activity regions that require social and moral reasoning (i.e., one's relationship to the whole of society). When one is using the logics needed for working with objects, the neural circuitry that considers others, emotion and context, is inactive. The finding that different regions of the brain are accessed for different logics is not in itself surprising or problematic. However, in a follow up study by Jack et al. involving WEIRD subjects, they found moral concern and analytical reasoning to be inversely related [15]. In particular, people biased toward analytical reasoning were also inclined to draw upon these same dehumanized logics in situations that call for contextual, humanized reasoning, particularly when the situation involved ambiguity. Other studies involving western educated and non-western educated subjects have shown that priming subjects to use analytical reasoning results in less humane and less altruistic decisions [16, 17].

While some engineering curricula require general education, the engineering appetite for technical knowledge in the U.S. has had a magnetic pull on our attention as predicted by the sociologist, Jürgen Habermas. He suggested that knowledge and the methods for acquiring it are constituted by the purpose, whether that is to control the physical world (*technical*), to work with people (*practical*) or to liberate one from their thinking (*emancipatory*). These knowledge-constituent interests produce three types of sciences that hold different assumptions, **Table 1**. Habermas predicted that technical understanding would take on a life of its own in modern societies, becoming the sole means, even when it is not fit for purpose [18]. Examples of using technical approaches for issues that require practical approaches are high-stakes educational tests for 'improving' education and the increasing use

| Type of science: | Natural | Social | Critical |
|---|---|---|---|
| Frame and habits of mind | Positivist, Analytical | Constructivist, Hermeneutic | Deconstructivist, Emancipatory |
| Interest | Technical: Predictable outcome of practical skills for employment | Practical/Meaning: Intellectual development and communication | Liberation*: Enlightenment to enact conscious choices |
| Assumptions about reality (ontology) | Reductionist: simple cause & effect; reduce variation in experiments to validate | Constructivist: complicated; attempt to examine all variables to see cause & effect | Holistic: complex; acknowledge unknowable variables create emergence |
| some practices derived from science | Engineering, western medicine | Education, counseling | Performing arts, spirituality |

**Liberation indicates the process by which models and paradigms are revealed as such, introducing both consciousness and choice where they were artificially constrained.*

**Table 1.**
*Habermas' types of sciences produced by his theorized knowledge-constitutive interests. From [19], adapted [20]. Used with permission.*

of technology to police society. These approaches amplify rather than solve the problems.

These patterns are pointing to a simple principle that legacy engineering education does not account for: Learning/knowing alters our minds [21]; structure conditions behavior. Most significantly for education, our neurological structure conditions our attention and thought. These emerging findings are weak signals of a concerning pattern: engineering education based on a foundation of reductionist science contains the risk of educating professionals who are diminished in their ability to see, feel and reason in humane, holistic ways. From Bohm,

> *"…each individual human being has been fragmented into a large number of separate and conflicting compartments, according to his different desires, aims, ambitions, loyalties, psychological characteristics, etc., to such an extent that it is generally accepted that some degree of neurosis is inevitable, …the attempt to live according to the notion that the fragments are really separate is, in essence, what has led to the growing series of extremely urgent crises that [are] confronting us today…this way of life has brought about pollution, destruction of the balance of nature, over-population, world-wide economic and political disorder, and the creation of an overall environment that is neither physically nor mentally healthy for most of the people who have to live in it." (p. 176 [7]).*

In short, a global engineering education at the emergence of Industry 5.0 must reframe engineering and develop a substantively new thinking as Einstein urged [22], lest we suffer a technology-enabled self-destruction.

## 2. Re-new thinking: embrace holism for engineering education

> *"A human being is a part of the whole, called by us 'Universe,' a part limited in time and space. He experiences himself, his thoughts and feelings as something separated from the rest— a kind of optical delusion of this consciousness. This delusion is a kind of prison for us, restricting us to our personal desires and to affection for a few persons nearest to us. Our task must be to free ourselves from this prison by widening our circle of compassion to embrace all living creatures and the whole nature in its beauty." (p. 20 [23]).*

What Einstein asserts is that the nature of the Universe is whole. Wholeness or Health, is a non-separable condition that exists prior to us. The fragmentation in 'western' science can be traced to Eurocentric philosophies from the 13-16th centuries, as described by Capra and Luisi [2]. By 1926, the South African statesman Jan Smuts advocated a return to the ancient Greek philosophy that he called "holism",

> *"the ultimate synthetic, ordering, organizing, regulative activity in the universe which accounts for all the structural groupings and synthesis in it, from the atom and the physico-chemical structures, [through] the cell and organisms, through Mind in animals, to Personality of man. The all-pervading and ever-increasing character of synthetic unity or wholeness in these structures leads to the concept of Holism as the fundamental activity underlying and co-ordinating all others, and to the view of the universe as a Holistic Universe." (p. 317 [24]).*

This notion of holism is not new; it has been embedded in indigenous cultures for centuries in many forms. For example, Native Americans like the Iroquois tribes believed that every decision should be made in consideration of how it will affect seven generations (i.e., 7 x 100 years) into the future, recognizing their present moment to be intertwined with a future one. They also viewed themselves as part of a web of life with nature as a collaborator, leading to a sustainable relationship with nature, prior to the genocide inflicted upon them by white men. As seen in such indigenous societies, adopting wholeness and health as the fundamental nature of reality opens onto a landscape of radically different interpretations, methods, practices and capacities.

Consider that our societal challenges, amplified by technology, are holistic in nature (e.g., anthropogenic climate change). They therefore require an engineering that is grounded in holism. In other words, reductionism is a mental model incommensurate with the phenomena it is attempting to address; by analogy, an engineer cannot incorrectly conceive of gravity as a force that operates parallel to the surface of the earth and expect a gravity-reliant design to function as planned. Even in cultures that are traditionally more holistic, such as the case for China, there is recent advocacy for holistic research approaches [25–27].

To be more effective in engineering, our challenge is to develop an organized practice of working with holism. Such a science would encompass and use reductionist knowledge when fit for purpose, but would expand our POV and methods in important ways. How would a holistic science differ from the legacy science? How would a holistic science provide benefit to society? We explore these questions in the following sections.

## 2.1 Holism paradigm v. fragmentation paradigm

If we take 'science' to be an organized study for the purpose of insight, a holistic science suggests a paradigm that radically differs from reductionist science. As can be seen in **Table 2**, the reductionist world view is one of separate objects that mechanistically interact; understanding comes through analyzing a system as simple, cause-and-effect interactions. A holistic world view embraces the whole of humanity and presumes unity, where forms arise though recursive interactions in the presence of energetic fields; understanding is inherently tentative and situational, producing heuristics. Reductionist principles are suitable for working with inanimate matter. They are not fit for working with living matter, humans or

| | **Reductionism** | **Holism** |
|---|---|---|
| Nature of reality | Separate objects, independent from one another, inanimate, consisting of fundamental building blocks | Inseparable, interconnected whole, animate, recursive patterns repeat at different scales ("fractal") |
| Behavioral phenomena | Mechanistic: interaction by simple, generalizable cause-and-effect relationships (e.g., Force = mass x acceleration); predictable as the sum of the part-level interactions, often linear | Emergent: from an innumerable, recursive interaction among self-organizing components in the presence of fields; unpredictable with qualities that are not necessarily found in the parts—non-linear, cyclic |
| Lens of understanding | Equilibrium/stasis or time-independence<br>Analysis– breaking down complicated into simple, quantifiable and verifiable principles | Non-equilibrium/order from chaos<br>Synthesis and Apprehension – Combining theory, action and observation in an ever expanding perception of patterns reflected in weak signals |

**Table 2.**
*The ontological assumptions of reductionism and holism.*

sentient beings. To point out the obvious, engineering to serve society inherently involves living beings.

Paradigms have far-reaching consequences due to the profound and often invisible effects that mental models have on our expectations, thoughts and actions. For this reason, the pioneering systems thinker, Donella Meadows, identified "transcending paradigms" as the highest leverage intervention for systemic change [28]. Many of our present-day societal challenges—pollution, climate change, poverty, economic inequity, education inequity, and health crises, emerge from the whole and simply cannot be addressed through reductionist means. Engineering education based on holism holds the possibility of aiding our ability to more effectively address global challenges. What might such an engineering education produce?

While we cannot clearly see into what a future of engineering from holism might produce, viewing holism and reductionism through the lens of Aristotle's causality, **Figure 1**, gives us a glimpse into a possible future. Aristotle, who assumed what we would now recognize as holism, modeled phenomena as emerging from the synthesis of four causalities: material, efficient, formal and final.

The causality in the physical domain concerns matter ("material cause") and techniques of shaping matter ("efficient cause"). The domain of relationships concerns structures that inform the phenomenon ("formal cause") and the ultimate ends or intent of the phenomenon ("final cause"). Engineering education in the U.S. has largely been focused on the physical domain, giving rise to the engineered world we inhabit today. What might it look like to design an engineering education with a holistic causality? What if we situated engineering as a sociotechnical discipline? What changes might we make if we centered our purpose or final cause to serve societal well-being? How would we change informing structures like Advisory Boards, faculty hiring and retention criteria or student acceptance criteria? With a final cause of health, how might we address the structural discrimination (e.g, laws, policies, practices) against those who have historically been denied social and economic power, such as Black and Brown bodied humans? How might education develop the whole neurological structure of human intelligence, cognitive and somatic? Clearly, this holism paradigm as a POV, opens our attention, causing us to literally see, understand, and act in different ways.

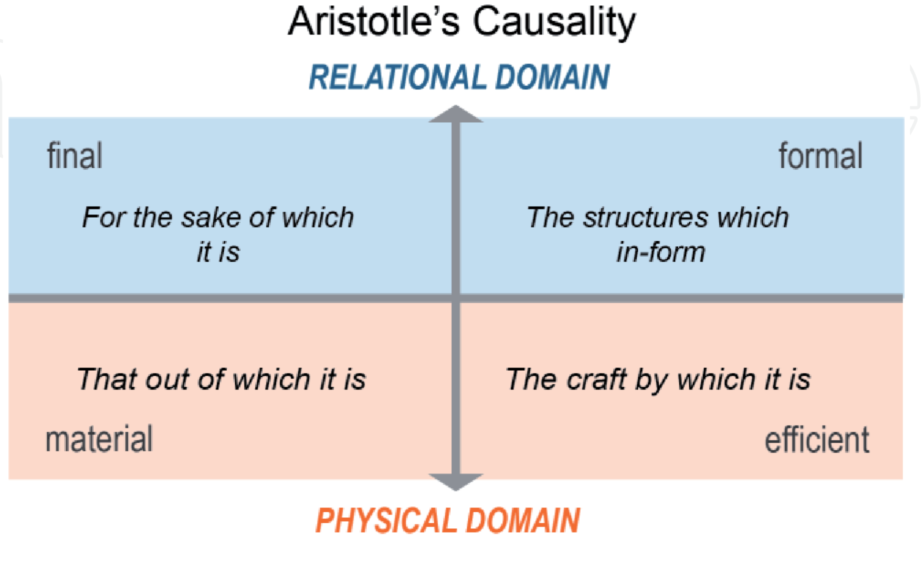


**Figure 1.**
*Aristotle's causality. The bottom half represents causality from the domain of the physical world, suitable to reductionism: material and efficient causes. The upper half is the domain of relationships that is suitable for holism.*

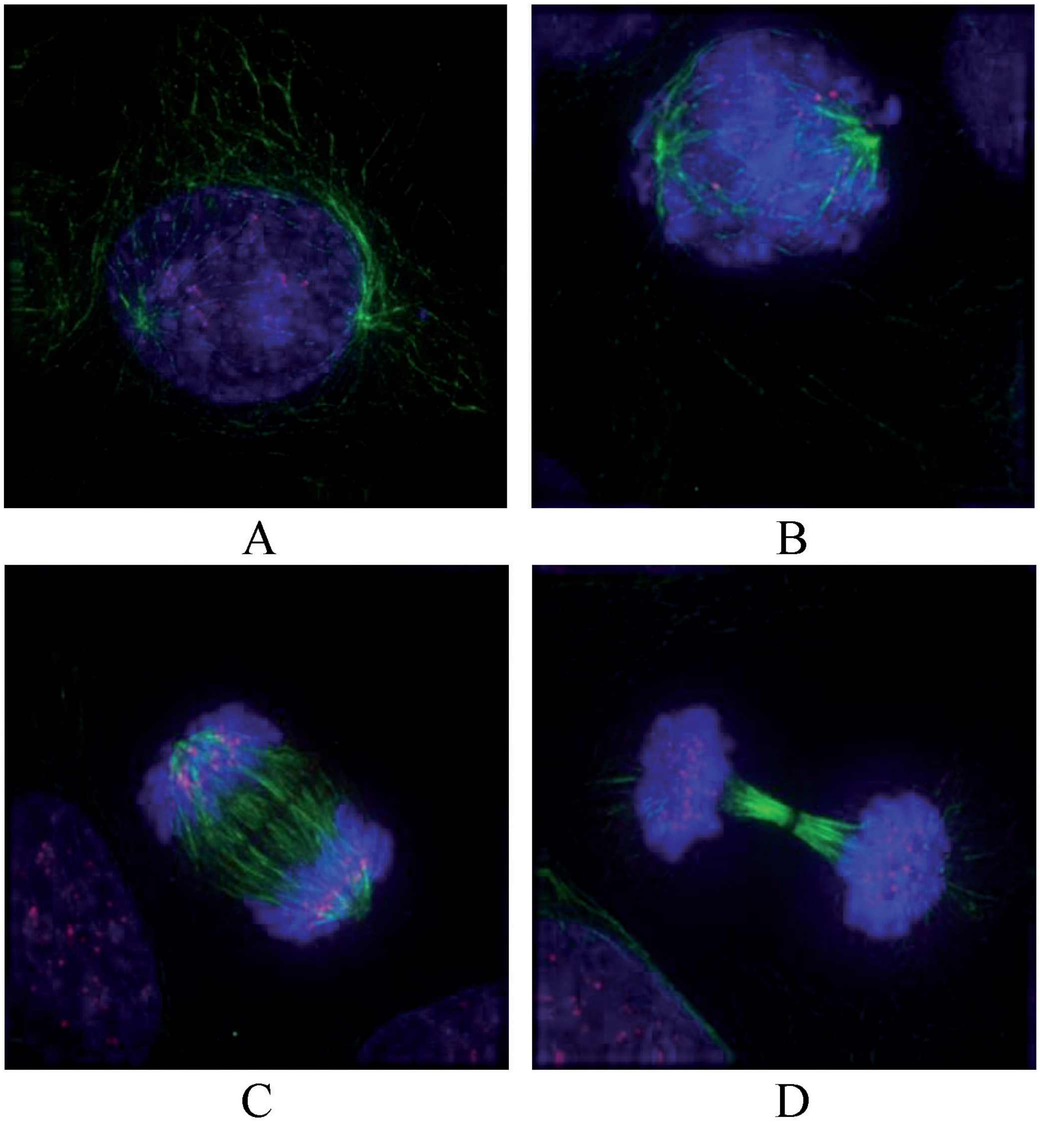


**Figure 2.**
*Four stages of cell mitosis. A. Prophase B. Prometaphase C. Anaphase D. Telophase. By Roy van Heesbeen - Delta Vision Roy van Heesbeen, Public Domain, https://commons.wikimedia.org/wiki/Mitosis.*

### 2.2 The cell as living system archetype

Let us consider how we might gain insight from a holism foundation by using a bacteria cell as an archetype. That is, we use here a biological model to illustrate a holistic lens for working with systems for any science, technology, engineering and math discipline. This living system cannot be separated from the universe, although we might consider the cell wall a boundary that defines the *system* from its *surroundings*. The term *system* is conceptual and refers to a set of interacting parts with a shared purpose—in the cell's case, the purpose is (presumably) living. At first glance, one might imagine that a living cell can be physically moved from its natural surroundings to a Petri dish. However, living requires the cell to exchange nutrients with its surroundings; in this way, we see that this living 'system' has an unbreakable connection with its 'surroundings'. The cell is living through its ability to maintain and replicate the conditions for its living. In what might be described as elaborate dances between molecules, the cell metabolizes nutrients and eliminates wastes or even replicates itself as shown in **Figure 2**. This property is termed *auto-poiesis* ('self creation') [29]. In this system archetype we see the following properties and behaviors:

- Interconnectedness which entails a network of countless *relationships*;
- *Self-organization* of the components through structural coupling in energetic *fields*;
- Recursive *patterns* of action among self-organizing components, which lead to emergent phenomena that are not directly traceable to its parts, such as autopoiesis.

The cell itself, viewed holistically, is an emergent form that is defined by its global, self-sustaining purpose. Using systems concepts, we view the cell as an open system, communicating across its boundary. This living organism provides insight as a metaphorical archetype for effectively working with systems. Its dynamically complex properties and behavior are fractal; the fractal nature of reality is captured in the aphorism by the microbiologist Albert Jan Kluyver, "From elephant to butyric acid bacterium—it is all the same." [30].

As indicated in **Figure 3**, the recursive patterns that result in autopoiesis exist at the scale of a single cell, an ecosystem of organisms and social culture. Using a systems lens, one can identify fields at each scale within which structures interact in self-organizing and recursive ways. At the scale of an ecosystem, nutrients are exchanged by producers, consumers and decomposers. Together, they symbiotically maintain the life-giving status of the ecosystem. Within an organizational scale, the social and historical expectations, norms and states of being--such as anger, fear, joy, or relaxation--function to create social fields. One can also identify structural analogs to the cell archetype in social systems. From a holism POV, the system is 'defined' by a shared global property, such as 'living' (cell & ecosystem), or student learning (college). At the cell level, the cell-wall creates the boundary that separates the conceptual system from the surroundings. For a college, the shared goal is student learning. Other structural features of an organization are the values and beliefs that govern peoples' behavior. In a social system, such as a college, these thought structures interact with the institutional structures of rules, policies, practices and identities to produce the phenomena of learning and enculturation.

In using the cell as the archetype, we are not claiming identical features found at the cell scale and at the societal scale. We're suggesting that the patterns of the cell provide insight for working with larger dynamically complex systems. The concept of a 'system' as being defined by a global intent is an example of a pattern that crosses scales: For the bacterium and organisms in the ecosystem, the shared intent is *living*; for something like a college, the shared intent is *learning*. Because of the

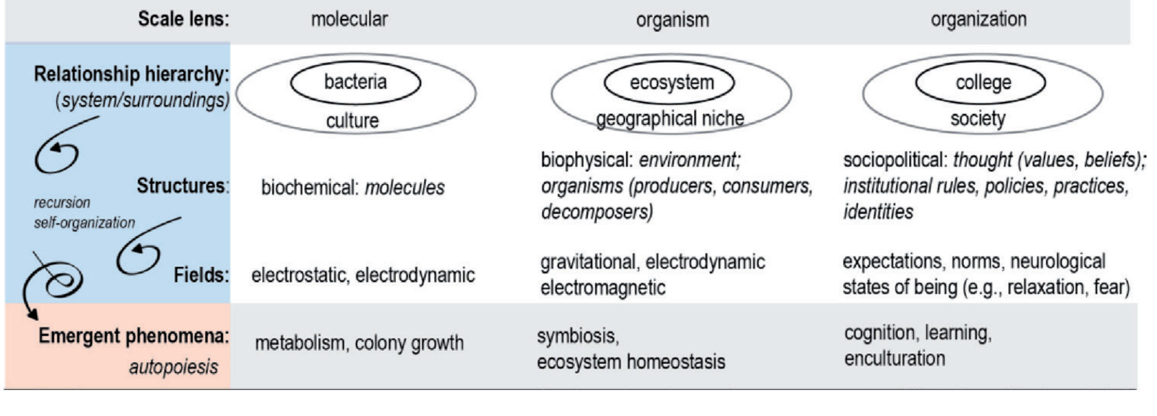


**Figure 3.**
*Fractal view of systems of different scales.*

fractal nature, working with dynamically complex phenomena would involve being attentive to *structures*, *patterns* of behavior, the quality of *relationships* and *field* conditions that might favor the emergence of one outcome over another.

What would be the appropriate scientific methods? In the next section, we will describe the relationship between methods and outcomes and suggest a holistic practice to account for this relationship.

### 2.3 Autopoiesis in scientific methodologies: knowledge informs the mind

As we consider the cell as an archetypal system for holistic science, one is likely to notice that there remains a great deal of unresolved mystery. What is causing these cells to undergo changes? Why exactly is it alive? What exactly is causing cells to differentiate in the emergence of a complex organism? Simply put, we do not know. Yet these questions highlight an essential difference in legacy science compared to a holistic science: reductionist science aims to answer questions, holistic science prioritizes achieving intended outcomes. Heuristic understanding occurs as a by-product in a holistic science, but it is secondary. In this way, holistic science is more aligned with engineering than reductionist science.

Holism recognizes that final cause has powerful and lasting ramifications; it functions as a seed out of which the tree and subsequent fruit arise. We can see the influence of final causality in the methods of reductionist science. They can be traced to Sir Francis Bacon, an English aristocrat and father of the empirical science method. Bacon advocated torture as a means to reveal truth [31]. He conceived of Nature as a female who hid her secrets from men, maintaining that "nature itself is something to be vexed and tortured, and that, once vexed and tortured, it will continue [as] the compliant slave of man" [32]. Bacon envisioned a utopian society, his formal causality, "for the Interpreting of Nature, and the Producing of Great and Marvelous Workes (sic) for the Benefit of Men" [33]. It was no doubt that his final cause of benefiting "man/men" was a reference to males of means, as women were often treated as property in 17th century England, a 14-year old version of which Bacon acquired as a wife at his age of 45 years [33]. Bacon represented an ethic where knowledge meant power and the interest of powerful men were deemed valuable by virtue of their (presumed) God-given superior social status. Bacon's cultural milieu, identity and position in society established a scientific practice that does not include questions about who defines the research questions and methods, whether they are socially just, or whether they are humane. Furthermore, Bacon's ideologies were influential in establishing thought in the U.S. which contributed to racists, sexist and inhumane 'scientific' practices; Bacon's ethics persist in U.S. science cultures through discriminatory practices and structures [34, 35]. For example, medical scientists in the U.S. abused African Americans for the sake of benefiting others [36–38], a rationale often used in cases of non-consensual experimentation on humans [39–41]. Such ideologies produced a biased 'science' [42] and scientists who believed that science cannot be an activity relegated to the "socially inferior" [38]; this assertion implies the reductionist fallacy that a condition that exists only in relationship to the whole (society), such as poverty, is explained by some inherent 'trait' of the individual. A science of holism would instead recognize any so-called "inferior" social condition in the U.S. as emerging from the historic, systemic effects of genocide, slavery, colonialism and legalized discrimination (e.g., see [43, 44]).

These reductionist patterns of thought and behavior ironically suggest an ontology of holism. Specifically, the condition of non-separability includes the observer as causal to what is 'observed.' Seeing co-arises with knowing so that the mind of the observer is literally *informed,* meaning that it has been physically formed, by knowledge. In other words, knowing is an autopoietic activity. From the POV of holism, it is not surprising that a view of the world as separate objects that will reveal their truths when tortured produces objectifying science, behaviors and conclusions.

In a holistic science, rather than attempt to eliminate distortion introduced by the observer, one accounts for it by holding a disposition of recursive inquiry throughout (p. 23 [45]), asking four essential questions: How do we know our understandings are accurate? How do we know whether our practice makes sense? How do we know whether we are acting morally right and appropriate in the circumstances? How do we know we are not self-deceptive in our responses?

## 3. Holistic science in action: navigating to shared aims

As mentioned, holistic science is concerned with achieving the intended aims. In this way, a holistic science is a theory in action which might be better described by the word *praxis*. It is more akin to the situational navigation used by ancient cultures in navigating across open bodies of water. In order to do so, they were attentive to nuanced changes in their environment, such as the direction and quality of wind, features in and on the water, the appearance of the night sky. In response to these signals, they continually adjusted their course so they might arrive at their destination. If one were conducting a traditional laboratory experiment, changing course during the experiment would most certainly ruin one's ability to validate the hypothesis. And, a holistic praxis, which would be more suited to working in human systems, would be more concerned with serving the shared human goals and less concerned, or not at all concerned with proving cause-and-effect. Methodologies like Critical Emancipatory Action Research, or Participatory Action Research, are holistic praxes. These social science approaches share the assumptions about the holistic, inseparable nature of reality, and purpose [46] as shown in **Figure 4**.

Participatory action methods are aimed at collectively achieving a social purpose and often used in community-based social change efforts or co-design. We submit that the assumptions and aims of the participatory action methods are more strongly aligned with those of engineering.

The conception of how change takes place when working in a social system starkly contrasts with reductionism. From reductionism, Newton's laws of motion condition us to believe that force must be applied to induce change ("An object in motion stays in motion unless it is acted on by a force."); Newton's laws are certainly useful in working with non-living matter. However, using force on people raises ethical dilemmas. Returning to the cell as a system archetype, the cause of action is mysterious, yet governed by the quality of relationships, structures and fields (**Table 3**).

As an educator, the notion that the quality of relationships, structures and fields condition change is easy to see. For example, imagine that learning is the change, a classroom the setting. Imagine that a human we call "student' is living remotely to their college. They lack the infrastructure for a stable, high-speed interconnection, yet the instructor has mandated "engagement" through synchronous course dialog. Imagine that the human we call "student" is in a social field of threat and fear because of the systemic conditions of a global pandemic and insufficient internet. In this scenario, it is perhaps obvious that the quality of the learning will be conditioned by the quality of connectedness, structures and fields.

What is less obvious is the profound shaping produced by the hidden value systems in our science.


| | objective experimental research | critical emancipatory participatory action research |
|---|---|---|
| *researcher perspective* | objective, outside of system of study; can be individual investigator | subjective, included within field of observation; requires collaboration, social. |
| *researcher narative* | third person (they, them, theirs) | first person (I, me, my) and second person (we, us, ours) |
| *epistemic paradigm* | Objective truth can be known through research methods and techniques sufficient to prove relationships; adherence to known or hypothesized relationships considered proof of validity. | Real human systems are dynamic and complex in ways that are unique to each situation; Ultimate criterion of "success" is whether it yields valid data that enables system to function more effectively. |
| *assumptions* | Methods are ethically neutral and objective; Principles and methods considered scientifically sound when implemented according to standard practices. | All research is carried out by people and therefore subject to biases at every point in the process; critical group dialogue used to uncover unexamined assumptions. |
| *aims* | Increased understanding of reality by discovering mechanistic interactions that can be generalized to larger populations; theory. | Functioning more effectively by freeing people from the unexamined constraints embedded in the language, modes of work and social relationships of power; practice. |
| *managing complexity* | Minimized through controlled experimental conditions | Acknowledged as inherent to real systems; accounted for through transparent documentation of situational factors |
| *process* | Variables and hypotheses fixed prior to initiating study; measurement of variables of interest through reliable instruments with predictable uncertainty. | Structured variables to be studied are not always predefined, may change through dialogue and course of research; reflexive dialogue used to find areas of conflict and explore them. |
| *outliers in data* | Considered aberrent if conflicting with expected behavior; Deleted if it can be justified through a known source of variation; Can be considered a point of inquiry of further investigation. | Considered an indication that something was left out of the original thinking on the change; Used as a point of further inquiry. |
| *results* | Generalizable to other situations. | Situational; provides insight through revealing situational patterns of behavior. |
| *research medium* | Empirical data, accurate and reliable instrumentation, standardized methods. | Attention that can interpenetrate and see connections between empirical, intuitive, theoretical and sensual data. |

**Figure 4.**
*Contrast of social science research approaches. Critical emancipatory action research is a collective form of action research. The numbers should be listed in sequential order.*



| | Reductionism | Holism |
|---|---|---|
| Governing principles of change | Magnitude and nature of applied force | The quality of relationships, structures and fields |
| Change metaphor | Leverage | Transformation (e.g. chemical reaction) |

**Table 3.**
*The nature of change from the POV of reductionism and holism.*

### 3.1 Hidden values live in the science of engineering education

As alluded to in the history of Francis Bacon, the value system of any science is embedded in its methods. As illustrated in **Figure 5**, the values that give rise to thought structures within the reductionist and holistic POV are quite different. **Figure 5** invites us

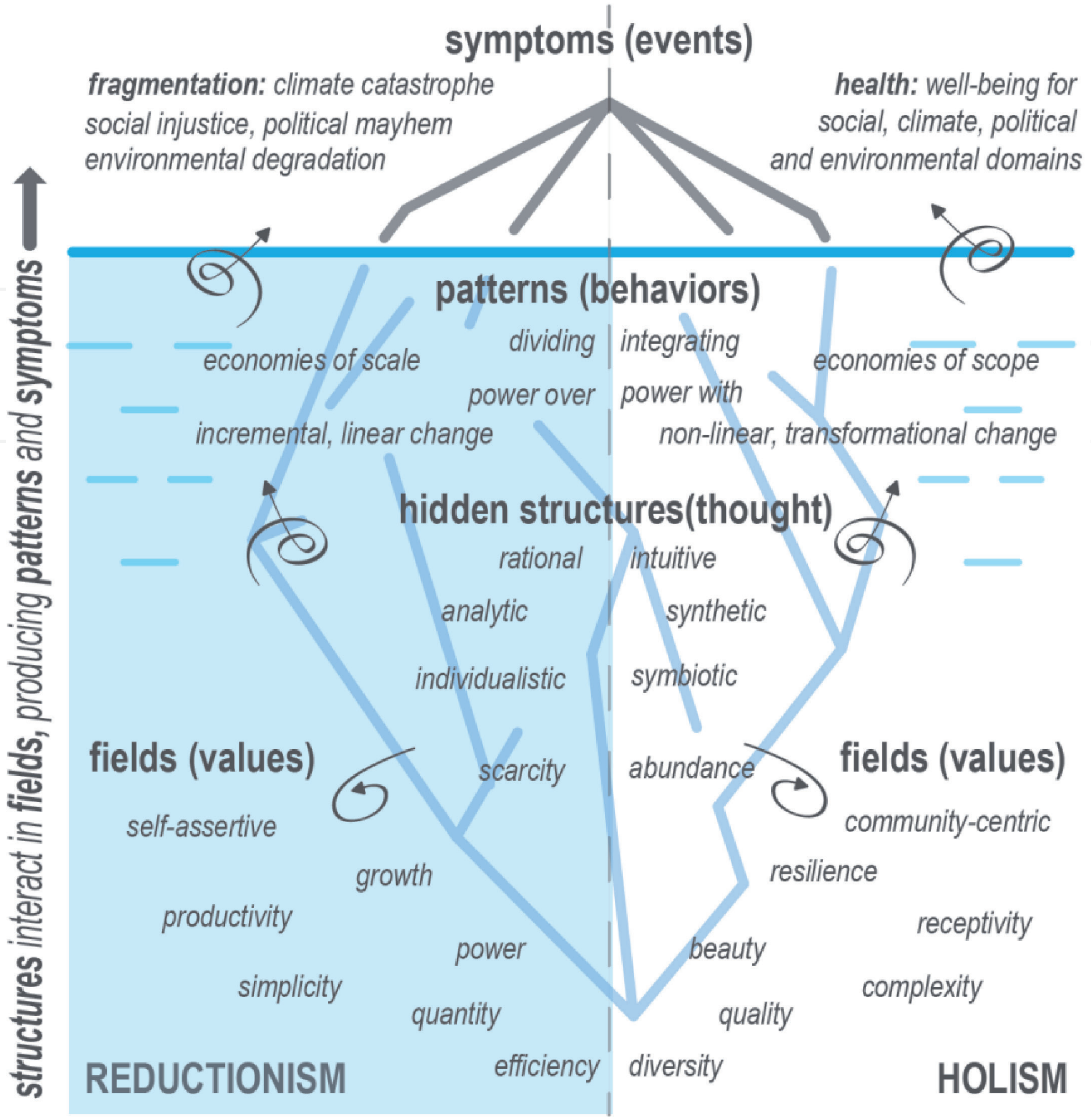


**Figure 5.**
*Reductionist and holistic values and thinking. The metaphor of an iceberg is in the background. Holism, while pictured for contrast on the right, encompasses the left and right areas of the figure. Adapted from [2, 48, 49].*

to see engineering education as a whole, arising from the force field produced by hidden values that instantiate thought structures and subsequent patterns of behavior.

**Figure 5** uses an iceberg as a metaphorical backdrop to call our attention to dynamic systemic patterns. Briefly, the inseparable coupling of gravity, the structure of the water molecule and the thermal conditions produce a buoyancy force that causes ~10% of the iceberg volume to protrude. The tip is symptomatic of dynamics that are hidden beneath the surface. One could destroy the tip (i.e., metaphorically address the symptoms) but it will be reproduced through the systemic dynamics: the gravitational field's coupling relationship with the $H_2O$ structures. Metaphorically, *values* play the role of gravity in the phenomenon that produces the tip of the iceberg; *thought structures* are like the water molecule structure; the *patterns of behavior* are like the buoyancy that results from water expanding upon freezing; the symptomatic events that emerge from the whole represent the tip. Our legacy engineering education has left us with symptoms of anthropogenic climate catastrophe, social injustice, stark inequities, political volatility and environmental degradation. We propose that an engineering education based on holism would instead produce Health.

What would an engineering education based on holism look like? We invite the global community to begin the creative process of answering that question. We offer a few thoughts, based on the principle that an autopoietic process will produce itself. In other words, the educational means of achieving the ends of health/wholeness must also have the quality of wholeness/health.

We first point out that holism includes reductionism. Reductionist science has value and we would first need to reflect on what we might conserve from our legacy methods. An ideal holistic engineering education would be balanced in its values and methods, producing discernment for choosing the methods that are fit for the purpose at hand. The value system in a Holism stance is captured in this simple imperative: *Honor the whole.* Here, the emphasis is on the whole, not just its parts. Similarly, an engineering education based on holism would embrace diversity in all its forms, not privileging one way of being over others, but dignifying all in an ethic of mutual respect. Such an education would honor the whole person as well, embracing emotions as natural and essential to meaningful learning, rather than something to suppress.

Some who feel strongly aligned with legacy science might argue that thought and emotion are separate realms with science falling within the domain of 'reason'. This logic is ironic on at least two counts. The first is that this view originated with Descartes. He deduced his idea to separate the intellect from intuition through *dreaming* [47], a highly irrational phenomenon. Secondly, from the second law of thermodynamics, we see that the spontaneous direction of change in the universe is in the direction of increasing diversity of states of being. Another way of looking at this second law principle is to conclude that where a lack of diversity exists, one can be assured that energy is being exerted to make that happen. While we are speaking in metaphor, the reader can readily test the clarity of this metaphor; do emotions arise spontaneously? (Here we are treating the different emotions as different states of being) Does it take energy, chemical or otherwise, to maintain a single emotional state? The same tests can be applied to other social systems. Let us say engineering education programs are somewhat uniform in their developmental outcomes; are there energetic forcing functions that produce such uniformity or is this uniformity occurring spontaneously? From these simple tests for coherence, we can see that a fragmented view is neither grounded in nor consistent with its own science; fragmentation is socially-constructed.

An engineering education derived from holism would be attentive to the quality of relationships in the learning environment. By relationships, we refer to the nature of what connects people: a holistic education would invite people to connect through purposes that transcend self-assertive interests. In the face of conflict people would turn to their shared purpose, larger than their self-interests, to resolve issues. One who viewed the world and work of an engineer as dynamically complex would expect conflict ("chaos") as a natural part of the process, rather than something to be eliminated. In other words, engineers would embrace the messy process of collaboration in social and political settings as a central and essential activity.

An engineering education that recognized the truth of holism would be attentive to the quality of structures that condition the learning. For example, the rise of academic capitalism [50] in the U.S. has institutionalized standardized testing for college entrance [51]. Because the standardized test was developed to validate a theory of white supremacy, this college entrance structure has produced structural discrimination against non-white populations. In the U.S., the engineering profession is depleted of diversity in perspectives by structural barriers at different scales: familial, classroom, institutional, regional, societal, and historical. To honor the whole of our collective humanity, an engineering education would do the painstaking work of revisioning just and equitable educational structures, policies and practices.

The work of revisioning just and equitable structures must recognize the fallacy of framing engineering as totally objective, meritocratic and free of social influences. This framing has been challenged by Cech and others in noting a Eurocentic discipline that fails to recognize the influence of race and gender on epistemologies and practice [52–54]. From the POV of holism, the framing is not a fact, it is an artifact: the autopoietic result of legacy science's originating mental models.

Honoring the whole would translate to honoring the whole of our humanity, recognizing the Descartes fallacy of "thinking" as primary. What we are learning from neuroscientists is that human intelligence is distributed throughout the body, rather than centrally controlled from the cerebral cortex as once believed. That is, the structure of our whole intelligence includes bodily sensations, often outside our conscious awareness. Feelings, presumed irrelevant to engineering curricula, are now recognized as essential to learning [55]. It is perhaps obvious that emotions are essential to empathy and moral reasoning; they are what humanizes us. A holistic engineering education would cultivate our ability to constructively work with our whole intelligence, managing our neurological states of being and honoring ways of knowing that include intuition, artistic expression and the lived experience. Of critical importance is cultivating our appetite for beauty. As Maxine Greene has taught us, beauty feeds the social imagination necessary to envision just alternatives to the world we have [56]. Given the autopoietic nature of our minds, the value of putting our attention on beauty is the possibility of generating beauty.

Finally, an engineering education from holism would develop skillful means in working with *social fields*. The notion of social fields was proposed by Lewin in his work with Holocaust survivors [57]. In his treatise, he used the analog and mathematics of electromagnetism to describe *social fields*—conceived as an energetic force that produced action at a distance—using reductionist concepts. However, the concept of an energetic social field can easily be seen in phenomena like social contagion or mob mentality. Additionally, the activity of mirror neural networks [58, 59] from a holistic POV confirms that shared, visceral human experiences can co-arise through observing another person; a witness can mirror the same neurological activation *as if* they were engaged in the observed activity. In terms of learning, a holistic engineering education would recognize how the quality of the social field conditions the ability for learning. For example, recent findings reveal the wide scale prevalence of trauma in the young adult population in the U.S. [60]. Such adverse childhood experiences become neurologically embodied, compromising peoples' ability to self-regulate and remain calm—the only state in which one can integrate new knowledge [61], **Figure 6**. Trauma effectively shrinks our "window of tolerance" for distress. An engineering education from holism would support learners' ability to manage their neurological state of being and metabolize adaptations that displace us from learning.

### 3.2 Preliminaries: where do we start?

In a world of urgency, we ironically feel our first action is to pause and reflect. If learning is an autopoietic action, we who have been conditioned through a western education may first need to unlearn. At minimum we will need to expand our ability to sense beyond what is presently available to us. The danger is that any action we take from our present condition will arise from the structures of our western education and thereby worsen the situation. So, our first need is to renounce the primacy of thought and cultivate a holistic neurological intelligence that includes abilities to sense and integrate our feelings. Perhaps coincident with unlearning

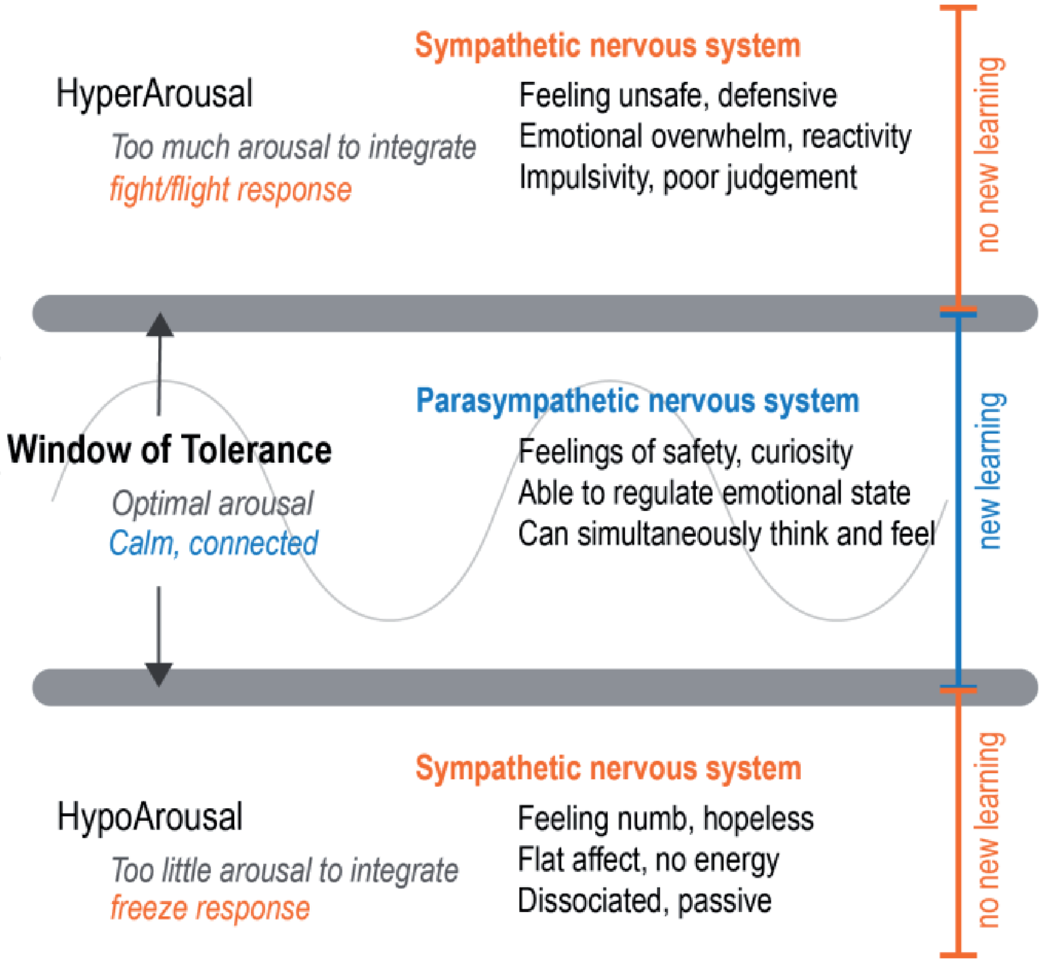


**Figure 6.**
*Nerve activation states from polyvagal theory. (Adapted from [61, 64]). The vertical axis represents the level of nervous system arousal, which naturally varies. One is able to self-regulate natural variations in arousal state within the window of tolerance. Chronic stress diminishes one's resilience (i.e., effectively shrinks the window of tolerance).*

the hidden dynamics of reductionism, we will need to apprehend the language and methods of holism. Engineering classrooms, as evidenced by syllabi, can draw on semantic frames which foster social fields of fear in classrooms [62]. We will need to re-language engineering if we desire safe social fields.

Another task is to identify what to conserve from reductionism. What balance of competencies are relevant for engineers to be humane and effective in a world of dynamic complexity? Surely reductionist science is important and applicable. What concepts do we preserve in a holistic engineering education? We, as an engineering community, need to do the difficult work to unlearn, rethink and learn. As educators, learning the skillful means of managing our neurological states of being would benefit ourselves and the people we call 'students.' Chari and Singh have developed such neuroscience-grounded training [63]. We have field-tested their methods in a recent online course; we and our students experienced their practices as significantly aiding our learning.

Within this new direction of holistic learning, we will also need to generate new methods for understanding our effectiveness. There are those who are skilled at working with managing change through holism [65]. However, the challenge for us disciples of reductionist science is to suspend judgment that arises from our unexamined mental models. A helpful heuristic is to notice when we react with strong emotions in the context of academic questions. That is an opportunity to reflect on the four essential questions: How do we know our understandings are accurate? How do we know whether our practice makes sense? How do we know whether we are acting morally right and appropriate in the circumstances? How do we know we are not self-deceptive in our responses?

### 3.3 A notional proposal for a holistic engineering learning method

We have laid out the case for a method of learning engineering grounded in a holistic world view. This means that any engineering curriculum would recognize its relationship to its local history and culture. At the same time, we imagine that engineering learning methods across cultures share some learning outcomes. Such outcomes, as we are suggesting in Section 3.2, would reflect not only the reductionist threshold capacities that the engineering community desires to preserve, but include those that are relevant to living in a dynamically complex world that is far from equilibrium. Such a systemic state, as Prigogine and Nicolis [66] have recognized, does not behave in linear ways, where the outcomes are predictable extensions of a plan; systems far from equilibrium are characterized by emergent, spontaneous changes of state which are non-linear, neither predictable nor sourced in the synthesis of the systems components [66]. Such state changes, while not predictable in the conventional meaning of the word, represent outcomes produced by the emergent conditions. The operative question in such systems becomes: What conditions favor the outcomes that we desire?

As a notional proposal, we suggest the threshold technical capacities and holistic enrichments for an engineering education grounded in holism as listed in **Table 4**. The detailed experience of a program based on these capacities is out-of-scope for this chapter, but available in a pending publication by the authors. However, we provide concrete example below. **Table 4** focuses on technical knowledge thresholds ("Reductionist technical content") that fall in the category of technical interests (**Table 1**). It also includes what we conceive of as enrichments ("Enriched by Holism") to support liberal and practical interests (**Table 1**). We acknowledge that **Table 4** is not comprehensive and omits many practical interests that we touch upon in our example below.

As stated, we would expect engineering education grounded in holism to reflect the rich diversity and cultural heritage that exists on the planet. However, to illustrate a practical example, consider this vignette of an example of an engineering learning method in the north eastern United States. It takes the form of a four-year experience.

The central tenets of this holistic learning method include:

1. everyone (students, faculty, staff, administrators) is a learner,

2. everyone is an educator,

3. we are not separate from the systems imagine: we are part of an interconnected web of relationships,

4. we are always practicing something in a recursive loop of theories, action and learning in the spirit of Critical emancipatory action research, **Figure 4**.

These tenets translate to a culture of mutual respect. Everyone is valuable and worthy of dignity, regardless of formal role. In a holism model, a community mantra might be, "Honor the whole." As a community member, one would feel a sense of care and responsibility for one another's well-being.

The faculty create the *least* structure required for learning. Of course, this would vary from institution to institution, but what is shared as humans is our innate

| | **Reductionist technical content preserved** | **Enriched by Holism** |
|---|---|---|
| Energetics | The first and second laws of thermodynamics and their implications<br>Newton's laws of linear and rotational motion applied to simple rigid bodies, Basic static and dynamic concepts and relationships | Power and energy flow within, between, among people and the planet (anthropogenic climate dynamics).<br>Conceptual understanding of force as a change mechanism in social and political systems (past, present and future). |
| Action in fields | Elementary chemical reactions near equilibrium conditions<br>Basic electrostatic and electrodynamic concepts and relationships | Far-from equilibrium dynamics (state changes, emergence, dynamic complexity).<br>Emergence in the presence of force fields (social, political); self-organization, structural coupling of outcomes to systems behavior. |
| Flow | One-dimensional flow of charge and thermal energy (steady and transient states)<br>Control through sensing and feedback | Neurological basis of sensing (perception, reception, interoception, proprioception).<br>Reflection, dialog and narrative in support of participatory, systems transformation.<br>Managing one's attention and state of being.<br>Making conscious choices. |
| Measurement | Math (curated competencies from: algebra, calculus, linear systems, statistics) | Ontological and epistemic boundaries of quantitative and qualitative data. Dynamic complexity (concept of strange attractor, curated systems behavior and properties of scale, scope, resilience). |
| Aliveness | Biology (curated set of principles about the structure and function of organisms, and ecosystems; metabolism, immune response). | Living systems dynamics (autopoiesis, recursion, self-organization, emergence, structural coupling).<br>Threshold conditions for thriving (well-ness, fairness, whole person and community development).<br>Art, joy and beauty as basis for creativity that is just and equitable. |

**Table 4.**
*Proposed threshold holistic engineering capacities, grouped into themes.*

motion toward learning when it is personally meaningful, it interests us and we can discover with a sense of psychological, emotional, academic and physical safety. The traditional "grading" system might be replaced with developmental milestones and reflection.

In this model, there would likely be an agreed-upon time where the parties convene to co-learn (i.e., a "class"), however, the primary means of learning would be collaborative (i.e., shared power), support self-organization, self-directed learning and peer-to-peer learning. The institutional schedule would structure blocks of time to accommodate collaborative project teams that transgress traditional boundaries.

Imagine that the curriculum was organized around the holistic themes of **Table 4**: *Energetics, Actions in fields, Flow, Measurement, Aliveness* and *Flow*. Over the four years, the curriculum would involve broader and deeper applications of these revisited themes considered at different scales. That is, we might conceive of ourselves as centered at the core of several interpenetrating systems, from most personal (the smallest scale) to transcendent (the whole): self, family, institutional, societal, historical and perhaps spiritual.

As a contextual backdrop, the present U.S. culture is simultaneously alive with the hope of freedom and toxified by its foundational history of genocide of indigenous people, enslavement of Black and Asian people, and violence against women. The myriad violences committed in building our nation have autopoietically reproduced through implicit cultural biases against people of color and women; such biases frequently escalate to lethal violence, such as the pattern of targeting Black men, women and children by law-enforcement agents, fragmenting our communities. A holistic engineering education in the U.S. historical culture could be organized around building the capacities listed in **Table 4** for the purpose of dissolving and healing these cultural dynamics while growing the Aliveness that we aspire to.

In the first year, among the many activities, learners would build capacities to access their whole neurology through such practices as mindfulness, meditation, yoga, martial arts or spiritual expression. Simultaneously, they would be learning about sensing, instrumentation and measurement by building electronic circuits. These human-centered and technological activities would be integrated to communicate the value in one's whole development. Such an integration of the fragmented Western so-called "mind"—abstract, cognitive thought—and so-called "body"—somatic sensations and feelings—would autopoietically produce holistic solutions.

They might also engage in learning history of the region and country, mapping the autopoietic results of these events as institutional structures, policies and practices at different scales: personal, social, regional, nation state, planetary. Simultaneously students would apply mathematics to simulate dynamic systems behavior through computer modeling. Using reflective dialog, they would make meaning together of systemic patterns, perhaps metabolizing residual effects in cases where their lives have been adversely affected.

They might develop their identity through weaving a story of their past, present and future selves in an engineered world. The sharing of these oral histories would be a celebrated community tradition. While developing their narratives of personal power, they would learn about power and energy viewed from the laws of thermodynamics. They would also learn how force works together with motion, equilibrium or stasis through Newton's laws of motion. Artistic expression, dance, music or theater would be practiced and celebrated with joy. Such activities serve to enrich their vision of who they are becoming and the influence they aspire to have in the world.

The theme of Aliveness could be addressed by studying Nature's designs. In addition to the basic concepts of chemistry and biology, students would learn the principles of autopoiesis and structural coupling. As an introduction to design, learners would be trained on the use of available prototyping tools so they can design a nature-inspired "Hopper." They would also draw connections between structural coupling in autopoiesis and inequities in our country's economic, health and environmental patterns. During this time, computational skills would be developed to analyze data.

In the following years, learners would return to the holistic themes of *Energetics, Action in fields, Flow, Measurement* and *Aliveness.* They may also expand their view and application of ideas to larger social scales. The learning might take the form of project-based learning in collaborative partnership with regional communities. For example, along with learning about energy and heat transfer, they could create data-based stock and flow maps of energy at institutional, regional and planetary scales. Such maps could serve as the basis to co-design highly-leveraged interventions for carbon-negative systems with community partners. Or, they may partner to co-develop technologies appropriate to the community setting. What is important in these later years is the process of collaborative discovery in the world outside of the campus.

The curriculum could include partnerships where learners live together situated on a site to demonstrate sustainable communities. They would continue embodied practices and learning related to *Energetics, Action in fields, Flow, Measurement* and *Aliveness.* They can deepen their technical knowledge around feedback and controls as they consider how these can be used to provide needed renewable power. Again, such questions of renewable power would be undertaken in metaphorical ways at different scales: self, family, institutions, community, society, history and future. On such demonstration sites, they could also deepen their practices by collaboratively working with regional partners to co-design carbon neutral exchanges of goods and services aimed at creating meaningful livelihood for those experiencing low income.

In this section, we have offered a glimpse into what learning engineering from holism might look like. In its essence, we have offered a vision of learning that is itself, autopoietic. That is, we have described a living, learning organization situated in the U.S. that sustains itself through a recursive return to global themes of *Energetics, Action in fields, Flow, Measurement and Aliveness,* including themselves as part of the systems they study. Projects, co-created and chosen by learners, figure prominently in the curriculum as does collaboration across boundaries. Embodied practices and dialog play central roles in dissolving power inequities in the learning environment; they enable people to manage their state for better learning and collaboration. Later years expand the scale of co-learning to encompass regional partnerships; sites serve as living laboratories to demonstrate the viability of beneficial, just and equitable alternatives to our current systems.

While this description may seem unrealistic, it is a narrative derived from our institution's myriad learning experiments over the last 20 years. The vision we describe above coheres to an explicit holistic model that was not a cohering principle of our institution's past curriculum. However, we offer it as a glimpse into one incarnation that is possible, recognizing it as something singular to our context. From the point of view of holism, we would expect a diversity of expressions of engineering curricula, relevant to the regional situation.

## 4. Conclusions

Reductionist science and practices are fit for limited purpose and have indeed resulted in the remarkable technological advances we see in Industry 5.0. However, emerging global patterns underscore the fact that our legacy reductionist science is insufficient to meet the moment. Disturbingly, a confluence of findings from different fields point to the pattern of self-replication in learning. An attention fixated on technical 'problems' creates an existence filled with technical problems. As predicted by Bateson [67], and later documented by O'Neil [68], without a profound educational shift, legacy science and engineering is likely to lead to self-destruction by extending the power of technology, uninformed by our humanity. Our challenge is to heed Einstein's imperative to adopt the paradigm of holism or face a future fraught with the increasing social, political, environmental dis-ease produced by fragmentation. Not only is holism more aligned with the nature of the universe, it more accurately describes the dynamically complex, sociotechnical realities that engineers work with. Its methods, drawing from existing social science praxes, are also more aligned in their assumptions and purpose to the profession of engineering. When we consider what a holistic engineering education might involve, we recognize that we can only see dimly. We have offered a working model organized around a recursive consideration of *Energetics, Action in fields, Flow, Measurement* and *Aliveness.* This proposed learning model, appropriate to our particular context, is only one of many incarnations of engineering education that we would expect to take form in a model of holism. There is a great deal of work to be done, yet we know that an engineering education for health/wholeness will itself honor the whole of ourselves and our societies. It will include reductionist science yet be attentive to the quality of relationships, structures and fields that condition what is learned. At minimum, an engineering education from holism will embrace our whole humanity, recovering our intrinsic motion toward beauty, joy, fairness and compassion—our vital humanizing qualities that are missing in our legacy engineering education.

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## Conflict of interest

The authors declare no conflict of interest.

## Declarations

The ideas in this chapter are solely those of the authors and do not necessarily represent those of the Coalition for Life Transformative Education.

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