A History of Fabrication and Action: Reconceptualising Engineering Literacy and the Engineer's Role

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Abstract

This paper reconceptualizes engineering literacy and the engineer's role by examining the conceptual history of engineering. It begins from the question of how to frame meaningful engineering responses to public crises, situated in the authors' own environmental engineering practice. It argues that this practice requires engineers who are literate in the historical ideas and contexts that have shaped accepted notions of the engineer's role – i.e. what engineers do and what engineering is for. By employing the method of conceptual history, the paper critiques the standard approach to technological and engineering literacy for perpetuating an image of engineering as fabrication. It finds that this image positions engineering as a pre-political activity in a stable natural order. In other words, it conceptually constrains engineers' agency and reflexivity concerning the aims and consequences of their work. Alternatively, the image of engineering arising from an embodied understanding – the engineer's self-conception – is explored for its potential for affording agency and reflexivity. The paper finds that this latter image of engineering as action positions engineers as makers of their own image and capable of enacting transitions in engineering practice within a framework of public leadership. The paper concludes that, without adjusting our framing, even well-intentioned, change-oriented projects risk reproducing the limitations embedded in received notions of engineering literacy and the engineer's role.

Keywords: engineering literacy, conceptual history, fabrication, action.

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Background: Technological Literacy as a Legacy of the 1960s

The project of technological and engineering literacy has seen several attempts at philosophical grounding over the last two decades [1], [2], [3]. In this paper, we put forward a historical perspective, framing the project of technological and engineering literacy as a legacy of the 1960s. Following Wisnioski [4], [5], we trace it to an engineering reform movement that sought to respond to the technologically framed 'crises' of the 1960s, such as infrastructure failure, nuclear risk, and ecological breakdown. Here the notion of 'crisis' was variously understood and interpreted as a crisis of confidence in engineering expertise, a tangible crisis in the natural and built world, a crisis of meaning among engineers regarding their purpose and role, or any combination of these. Wisnioski has shown how reformers sought to make sense of the engineer's role and responsibility in these 'crises' using an emergent vocabulary of technology, shaped by popular texts – such as Lewis Mumford's *Technics and Civilization* (1934) and Jacques Ellul's *The Technological Society* (1954) – as well as popular culture and broader societal conversations [5]. With this vocabulary of technology, they discerned and articulated a need for greater technological literacy among both engineers [6], [7] and the public at large [8], [9]. They emerged from these 'crises' with the aim of enrolling engineers and publics alike in a shared understanding of the increasingly decisive role of technology and – by extension – engineering in American life. As Wisnioski found, this shared understanding "almost always took the form of epochal thought that explained the engineer's role in the past, present, and future of *technological* society" (own emphasis) [5, p. 760].

Thus, central to the 1960s engineering reform movement was the metaphor 'engineering produces technology'[1]. As a metaphor, it positions engineers as the makers of our technological world and implicates the engineer and their profession in its 'crises'. Reformers of different stripes shared a common strategy of employing this metaphor as a normative device. Uniting diverse interests and viewpoints under the banner of 'engineering

[1] Leading engineering theorists and professional bodies have adopted this notion. For example, Walter Vincenti, once defined engineering "as the practice of organizing the design, *production*, and operation *of an artifact* or process that transforms the physical work to some recognised human end" [10, pp. 18–19] (our emphasis). See also the National Academy of Engineering website FAQ section which states: "Engineers are men and women who create new products" [11].

produces technology', they sought to establish this particular understanding of the engineer's role via a program of 'technological and engineering literacy' [12]. Their shared aim was to engender a sense of ethical and social responsibility within the profession and thereby motivate meaningful engineering responses to the problems of their world [5]. As Wisnioski describes it, "they were seeking to implement ideas formed by intellectuals into a new grounding of engineering practice" [5, p. 759].

These borrowed ideas were considered essential to the project of technological literacy. The 1960s reform movement demonstrated that an actionable and standardizable literacy project required a stable and coherent conceptual schema that expresses an enduring understanding of a topic, and how it relates to other relevant topics, across a diverse range of local contexts. In other words, literacy was understood as *downstream* of a stable understanding of certain aspects of our world and the availability of language – a vocabulary – to represent it. The history and philosophy of technology supplied the canonical body of knowledge for the project of technological literacy launched by the 1960s reform movement [1], [9].

Context: Contemporary Projects of Engineering Literacy

With this historical background in mind, we seek to question the ongoing usefulness of the metaphor 'engineering produces technology' as a shorthand for both the subject matter of engineering literacy and the substance of the engineer's role. We note that prior TELPhE proceedings [2], [3] have shown the potential for distinguishing engineering literacy from technological literacy via an emergent body of knowledge in engineering studies and the philosophy of engineering. However, we find that interpretations and applications remain within the metaphor of 'engineering produces technology'. As one study itself concluded: "engineering literacy may be thought of as a branch *from* technological literacy" (own emphasis) [3, p. 7].

In this paper, we approach this question as researchers, educators and practitioners in environmental engineering and humanities. We articulate it in the context of our own actions responding to technologically framed environmental crises by engaging in engineering reform. Thus, the technological and engineering literacy project has a particular contemporary meaning for us. To orient the reader in our particular context we can point to a number of familiar landmarks in the contemporary landscape of engineering practice.

Firstly, we find that engineering reformers, among whom we count ourselves, have again turned to a program of engineering literacy to engender a response to the 'negative' consequences of engineering. Take for instance the initiatives under the banner of 'engineering education for sustainable development (EESD)'. Key forums for this reform movement include a bi-annual conference, a series of political declarations (the *Barcelona Declaration,* 2004 and the *Cork Amendment to the Barcelona Declaration,* 2021 [13]), and academic and professional publications [14], [15], [16], [17], [18], [19]. The average engineer might encounter this project of engineering literacy in the events and publications of professional associations, such as Engineers Australia's 'Climate Smart Engineering' annual conference; the Institution of Structural Engineers' (IStructE) 'Climate Emergency Conference'; the Royal Academy of Engineering's *Review of the teaching of sustainability in UK engineering higher education* (2024); and IStructE's *The structural engineer's responsibility in this climate emergency* (2020).

We further note that reformers continue to make sense of the engineer's role and responsibility in environmental crises using the vocabulary of technology. In other words, the metaphor 'engineering produces technology' is again the normative device, used to frame the engineer's role in terms of their 'responsibility' or 'obligation' as 'producers of technology'. For example, the *Review of the teaching of sustainability in UK engineering higher education* articulates the engineer's role and responsibility as:

> "The *responsibility* is two-fold. We must first acknowledge that while engineering has *delivered* huge benefits to humankind through many *technological advances* that have improved the standard of living… much of that change has not been sustainable or without *significant environmental impact*… The second area of responsibility is as part of the solution to the… *crisis*" [12, p. 7] (own emphasis).

Furthermore, this responsibility or obligation is often articulated as one that is necessitated by the consequences of engineering work. For example, *The structural engineer's responsibility in this climate emergency* states that, owing to "how much structural engineering contributes towards climate change", it is the engineer's "duty… to start acting" [20, pp. 10–11] .

In our judgement, this 'necessary responsibility' framing has so consistently fallen short of expectations – in over a half century of use – that it justifies a fundamental rethinking. To support this claim, the authors can also point to an ongoing, well-documented shortfall in meaningful responses to climate change [21], [22], [23]. Thus, we begin from the premise that, as a normative framing device, it has proven to be inadequate for generating meaningful engineering responses to crises.

Aim and Overview: An Effective Framing for Engineering Reform

With this positionality, we search for a historically and philosophically grounded explanation for why engineering reform framed as a 'necessary responsibility' consistently falls short. We then use this explanation to guide us toward a more effective framing that we can employ in our own environmental engineering practice. We first examine the conceptual lineage of the metaphor 'engineering produces technology' and find that it is rooted in the concept of '*techné*' and its corresponding Aristotelian conceptual schema. We outline how this stable and enduring schema has been consistently employed by social and political elites to define the engineer's role in terms of external, politically defined ends. We further demonstrate how the ongoing influence of this schema has served to conceptually anchor the engineer's role in an ancient political and natural order that withholds engineers' agency and reflexivity concerning the aims and consequences of their work. Thus, we explain the practical limitations of the 'necessary responsibility' framing in terms of its historical and conceptual limitations.

With this explanation in mind, we sought a conceptualization of the engineer's role that has historically and conceptually granted engineers agency and reflexivity. We found this in the engineer's self-conception. Firstly, it affords an open and expansive view of engineering rooted in the concept of '*ingenium*' and expressed in a vocabulary of magic, or change. Secondly, the 21st century has seen this embodied understanding of self-made '*ingeniators*' put down in writing as a coherent conceptual schema. We propose that in these two respects the engineer's self-conception can provide a firm basis for a more effective framing of engineering responses to public crises. We further discuss what it would mean for our environmental engineering practice and a renewed project of engineering reform. One that is no longer framed as a necessary responsibility to comply with externally defined obligations but rather found in the metaphor 'engineering produces change'.

Question and Method: Turning to Conceptual History

What are the consequences of maintaining a technologically framed conception of engineering literacy? Is there an alternative, and what does it offer? To investigate these questions, we turn to the method of conceptual history. This historical method seeks to understand how ideas change over time. We use it to trace how the idea of engineering has been understood in different historical contexts and reinterpreted across time, both maintaining continuity and introducing change to the way in which engineering is understood and practiced. We anchor our conceptual history in the communities that have sought to influence the meaning of engineering over time through influential written texts – while noting that this affords only a partial window into the past. By locating these communities and texts, we can demystify – recognizing ourselves and our world – and explore marginal views that offer paths not travelled. We begin by tracing the history of an idea of engineering that underwrites today's technological and engineering literacy project.

Findings: A History of Fabrication and Action

"... it is important to be aware how decisively the technological world we live in, or perhaps begin to live in, differs from the mechanized world as it arose with the Industrial Revolution. This difference corresponds essentially to the difference between action and fabrication." [24, p. 59]

A History of Fabrication, or Useful Work

The conceptual lineage of the idea of engineering that underpins today's technological and engineering literacy project can be traced via culturally and politically authoritative texts. These include the works of science policymakers in 20th century USA, 18th century British political economists, and Ancient Greek philosophers of the Socratic school[2]. Their works, and the milieu they represented, have in turn been studied for both the content and influence of ideas they espoused[3]. Taken together, we can locate in these works an enduring image of engineering as 'fabrication', or useful work, anchored in a set of related concepts (e.g. craft, artifact, nature, politics etc.) that have been retained and reinterpreted across different historical and intellectual contexts (Table 1).

[2] Key texts include Presidential science advisor Vannevar Bush's 'The Endless Frontier' (1945); and the political economist Adam Smith's 'The Wealth of Nations' (1776); and the collected works of the major Ancient Greek philosopher Aristotle.

[3] In this study, we rely on the history of the idea of 'applied science', 'applied research', and 'innovation' by historians of technology (specifically Godin, Williams, Engel, and Kline); the history of the idea of 'industrialisation' and 'political economy' by historians of technology and economics (specifically Wilson, Wolloch, and Smith); and the elaboration of the concept of techné in Aristotle's philosophy by philosophers of technology (specifically Arendt and Arnâutu).

Table 1 The vocabulary of technology: summary of key models and their shared conceptual schema

Key concepts	**Ancient Greek crafts model**	**18th century industrial arts model**	**20th century applied science model**
Craftsman	Craftsmen make artifacts [24].	Technical workers make commercial industrial products [25].	Engineers and scientists make applied-scientific technologies in the "trading zone of technoscience" [26, p. 43].
Craft	The crafts make artifacts for our biological needs [24].	The industrial arts produce commercial products for market needs [27].	The applied sciences provide technical knowledge and innovation for the needs of the nation [28].
Artifact	An artifact is a means to an end of biological necessity [29].	A commercial industrial product is a means to an end of material prosperity, or "universal opulence" [25].	A technology is a means to the strategic ends of policymakers [30].
Nature	Nature is a cause in itself, self-perpetuating and self-regulating. It is essentially separate from the human-built world which is dependent on and enclosed by it [24].		
	Artifacts are fabricated from matter[4] [29].	Products are fabricated from natural resources, or "natural capital" [31].	Technologies are fabricated from the laws of nature [30].
Politics	Politics is circumscribed within the human artifice and confined to the stage of human history [24].		
	The aims of craftsmen are subsumed to external ends[5], set by others deemed capable of citizenship and political action (*praxis*)[6] [29].	The aims of inventors are directed by the needs of the market (and marketing) set by the self-interest of consumers [27].	The aims of applied research are directed by national interests set by professional political decision-makers (i.e. policymakers) [32].
Thought	Free men, as political actors, are encouraged to engage in contemplation (*theoria)* [24].	Economists study the national economy to elaborate theories for economic growth [25].	Scientists conduct 'pure science' or 'basic science' (*episteme*) and thereby reveal the laws of nature [28].

[4] This refers to the passage: "…matter… determines the production in the making and producing of any work of art, and in… a part of the product is present…" in in Aristotle's 'Metaphysics' (1034a) as cited by Arnâutu [29].

[5] This refers to the passage: "making aims at an end distinct from the act of making" in Aristotle's 'Nicomachean Ethics' (Book VI, 1140b) as cited by Arnâutu [29].

[6] This refers to the passages "there are some arts whose products are not judged of solely, or best, by the artists themselves" and "the best form of state will not admit [the artisan class] to citizenship" in Aristotle's 'Politics' (1282a, 1277b-1278a) as cited by Arnâutu [29].

We find that 'modern' conceptualizations of engineering adopt an archetypal image of 'craftsmen making artifacts' dating back to ancient times. In other words, we can take this conceptual schema to represent the metaphor of 'engineering produces technology' in its most elementary and definitive form. In this manner, we locate the conceptual schema of today's technological and engineering literacy project in the philosophical framework of the Socratic school. We find that its component concepts work together to impose a particular order on the way we think about engineering and its relationship to the world. Specifically, we identified two key features of the Aristotelian conceptual schema that are worth understanding if we are to arrive at a philosophically and historically grounded answer to the question that motivates this paper.

Artifacts and politics: Limiting the engineer's agency

The first feature established a pattern for the aims of 'making' to be subsumed to external 'ends', set by others deemed capable of contemplation and thus prudent political action. We trace this to the social and political order set out in Aristotle's philosophy, which placed craftsmen in its lower tiers. It was reasoned that, since craftsmen were 'slaves' to biological necessity they were incapable of neither political action (*praxis*) nor contemplation (*theoria)* [33]. At the apex of this social and political order were the free men whose economic security enabled them to participate in public-political life (the *polis*). It was reasoned that 'freedom' from activities driven by biological necessity was a necessary condition for participation in public life and, by extension, politics. These social distinctions – based on the capacity for political action – saw fabrication, or useful work, designated as a pre-political activity. 'Fabrication' in this context encompassed a broad set of roles relying on craft or art (*techne*) which included craftsmen (*banausos*), builders (*tektōn*), master builders (*architekton*), and machinists (*mechanikoi*) [34].

In its terms and definitions, Aristotle's philosophy erected an enduring (conceptual) boundary between practical 'makers' and political decision-making which has consistently excluded the former from the latter. For example, this conceptual boundary remained firmly intact in reinterpretation of crafts as an industrial art by 18th century British political economists. 'Makers' were reinterpreted as inventors whose aims were externally directed by the needs of the market (and later, marketing). Their inventions, i.e. artifacts, were reinterpreted as commercial-industrial products, subject to and ordered by economic laws. Craft activities were rationalized and produced on an industrial scale by technical workers whose value was externally measured in objective terms such as cost efficiency and time productivity [35].

Likewise, when the industrial arts were reinterpreted as applied sciences by 20th century US science policymakers, they retained the basic distinctions and relationships between 'artifacts' and 'politics' from the Aristotelian schema [36]. In their authoritative image of technological innovation, scientists and engineers develop scientific technologies in the national interest. Professional political decision-makers (i.e. policymakers) direct the work of federally funded scientists and engineers toward these politically defined national interests [32]. The work of engineers remains subsumed to external purposes or 'ends' set by others who are the sole political actors in this relationship, consistent with the basic Aristotelian schema.

With these examples of influential models of engineering, we mean to underscore the pervasiveness of conceptualizations of engineering as a pre-political activity and engineers as apolitical makers of products or developers of technologies. It points to the first failure mode we identify in efforts to engineer a meaningful response to public crises. Here we use the term 'failure mode' in its engineering sense of the discernable conditions in which a design can fail in performing its intended function. We draw upon the work of philosopher Carl Mitcham in thinking through why engineering has encountered recurrent difficulties in establishing a clear sense of public responsibility among engineers. Mitcham reasoned that the exemplar professions of law and medicine serve ends "integral" [37, p. 339] to their profession (e.g. lawyers serve the ends of justice, doctors serve the ends of health). However, on these terms engineering is a "philosophically inadequate profession" [37, p. 339] as it serves ends that are not integral to it (e.g. "the advancement of commercial and industrial interests" [37, p. 345])[7]. We have linked this philosophical inadequacy – the subsuming of engineering work to externally defined ends[8] – to the enduring influence of the Aristotelian conceptual schema on how we conceptualize the engineer's role.

[7] We relate this philosophical inadequacy to the cultural authority of the image of engineering as fabrication, e.g. where craftsmen serve the ends of biological necessity, technical professionals serve the ends of the market, and applied scientists serve the ends of the national interest.

[8] Take for instance, the IStructE's report quoted earlier which states: "it's clearly important that we all play our part in bringing global emissions down to the levels demanded by *governments and the IPCC*." (own emphasis) [20, p. 10].

Mitcham's analysis suggests that a more effective approach to reform would involve presenting engineering as serving ends that are integral to it. In other words, it recommends that engineering responses to public crises be expressed not in terms of the engineer's role or responsibility, but rather in terms of the engineer's purpose or actions. This framing would grant, rather than deny, agency to engineers in (re)setting the aims of engineering work. Our analysis has shown that this approach would require a departure from the prevasive image of engineering as fabrication and the vocabulary of technology that constitutes and enacts it.

Craft and nature: Limiting the engineer's reflexivity

A second failure mode relates to the Aristotelian concept of nature (*physics*). In Aristotle's philosophy, nature is understood as a cause in itself; self-regulating, self-perpetuating, and eternal. Nature is essentially separate from and beyond human affairs and craft is without consequences for the natural order. The image of craftsmen making artifacts suggests two specific interfaces with nature: one where nature provides the material for fabrication and the other where we 'make' out of biological necessity in our own nature. This feature was reproduced in the industrial arts model of 18th century British political economists, translated as 'natural resources' on the one hand, and 'self-interest' on the other. Similarly, the 20th century US applied science model continued this conceptual tradition by positioning nature as a repository of laws revealed by scientists, on the one hand, and engineers as driven to 'apply science' to the needs of the nation, on the other.

This points to our second failure mode. It was described by the German American thinker Hannah Arendt in thinking through the philosophical implications of the atom bomb. She reasoned that the reality of the bomb amounted to a break with the Aristotelian conceptual schema, requiring a new vocabulary. Contrary to the Aristotelian order of things, engineers act *into* nature when they initiate processes whose consequences extend into the world we share, and whose consequences are inherently uncertain. In this sense, the image of engineering as 'craft without consequences' could not adequately represent the capacities and real expressions of engineering in the world. Nor could we simply call attention to the consequences of engineering[9] without thinking through what it means for our conception of the relationship between engineering and the environment – beyond the highly durable Aristotelian conception of 'making' with and within 'nature'. For Arendt, it was essential to

[9] Take for instance, the IStructE's report quoted earlier which states: "This means recognising the long-term aspect of our work and minimising our damage to the *environment*" (own emphasis) [20, p. 11].

think through the distinction between fabrication (making durable artifacts) and action (initiating new beginnings in a common world).

Arendt's analysis suggests that we should seek another conceptual schema to make sense of public crises concerning the consequences of engineering work. Furthermore, by emphasizing the interrelationships and coherence among key concepts, her analysis suggests that any reconceptualization of engineering requires attending to the whole, i.e. extending this reconceptualization to related concepts and ensuring overall coherence. Furthermore, the importance of a strong empirical grounding is also highlighted in her analysis, where new realities at the leading edge of engineering necessitate concepts that can better 'fit' (i.e. represent) these new realities. A better 'fit' would first and foremost entail a framing of the engineer's role that grants, rather than denies, reflexivity to engineers in response to the consequences of engineering work.

In summary, the enduring conceptual boundary between engineering and politics, and enduring conception of engineering as 'craft without consequences', in part, explains the lack of meaningful engineering responses to public crises associated with engineering work. Furthermore, this conceptual schema is only strengthened by the words and images employed by reformers in their framing of the engineer's public role. By using the vocabulary of technology and the image of engineering as fabrication in their projects of engineering literacy, reformers merely reinforce the status quo. They are merely attempting to define a public-political role for engineers concerning the environmental consequences of their work using the very concepts that have long denied such a role and consequence. In this manner, we endorse Aravena-Reyes' argument that:

> "…returning to the etymological roots of word technology can help elucidate the reasons that led engineering to become a passive agent that solves problems without questioning the constitutive order of the active agents that created these problems in the first place" [38, p. 125].

In other words, we can trace the shortcomings of engineering reforms to an unquestioning acceptance and "appropriation" [5, p. 759] of the vocabulary of technology and its corresponding conceptual schema. It amounts to no more than an ineffective attempt to change an externally constituted and enacted order of things using the very words and images which serve to constitute and enact that order.

A social and political elites' conception of engineering

This history of engineering as fabrication underscores the authoritative role of certain intellectual communities, belonging to the social and political elites of their time, in shaping accepted notions of engineering. At the same time, historical analysis has also sought to introduce sense of contingency to the idea of engineering. For example, that the Aristotelian conceptual schema was in part influenced by Socrates' death at the hands of the Athenian democracy and sought to make the world safe for philosophy. In their political need to place philosophy at the apex of their value hierarchy, they reinforced the lowly status of craft, akin to domestic servitude, in the eyes of ancient Greek society. Or that the written works of political economists were motivated by their own objectives to make the world safe from the predatory trade practices of powerful states. Or that US science policymakers were motivated by political aims of professional status building to make the world safe for scientific technology. Despite these intimations of contingent political motivations, the ideas of these intellectual communities have ordered the way we think about engineering well beyond the historical events that gave rise to them. It poses the question 'who *should* decide what counts as engineering, and how?'.

On the one hand, the conceptualization of the engineer's role inferred by these authoritative texts were widely embraced by engineers themselves. In the present day, engineering schools and professional institutions have embraced the 20th century applied science model of US science policymakers and its vision of technoscientists innovating, regulating, and educating on applied-scientific technologies [39]. A century earlier, a fledgling engineering profession and system of formal technical education embraced the 18th century political economists' industrial arts model of a technical profession producing and standardizing commercial products[10] [41]. The 1960s engineering reform movement followed suit, embracing the ideas of 20th century philosophers and historians of technology and their vocabulary of technology [6].

On the other hand, the capacity for engineers to question authoritative texts was demonstrated on the very grounds upon which our notion of technological literacy was established – the history of technology. In authoritative venues like the journal *Technology & Culture*, engineers challenged academic descriptions of engineering for insufficiently

[10] For example, the UK Institution of Civil Engineers' Royal Charter at its founding in1828 defined engineering as "the art of directing the great sources of power in nature for the use and convenience of man" [40, p. 160].

representing “recent practical experience” [42, p. 470] or “real people in real situations” [43, p. 680]. They criticized the work of academic historians, writing “I cannot share that view” [44, p. 508] or “I do not notice there much resemblance to the engineering world in which I worked” [45, p. 853]. They emphasized again and again that, owing to a “difficulty learning how engineers think and feel” [43, p. 682], academic historians “may find themselves caught up in fruitless doctrinaire debates” [43, p. 680].

A History of Action, or Magic that Works

This curious episode sheds light on a path not travelled in our standard idea of engineering. Namely, it surfaces a certain embodied understanding of engineering that has seldom received scholarly treatment. In terms of a core concept and vocabulary, we can locate an early written representation in the Latin root *ingenium* and an accompanying vocabulary of magic. The first use of this term is attributed to the Christian theologian Tertullian in c. 200 C.E. who referred to the battering ram as a “*novum extraneum ingenium*” [34, p. 82], meaning a novel, strange “invention or product of genius” [34, p. xxi]. There is a close association of *ingeniators* – those who produced such *ingenum* – with war and military campaigns. This association dates back to the ancient Greek figure Archimedes of Syracuse and forward to the Italian Renaissance master Leonardo da Vinci, the first engineering school in the US, the US Military Academy at West Point, and beyond. In this manner, an image of engineering as action, was born and nurtured in that most heightened of political actions, war, which has been described as a “political instrument” for “the continuation of policy by other means” [46, p. 37].

Engineering on its own terms

Over a thousand years after Tertullian’s use of the term *ingenium*, it reappeared in 15th century Italian Renaissance writings as “the ‘ingegno’ of the great engineer and architect who conceives and executes the plot – one in which human brilliance replicates one of the standard feats of the magicians” [47, p. 64]. In the vocabulary of magic[11], Italian Renaissance writers emphasized the engineer’s capacity for strange wit and ingenuity and the wonder resulting from their actions, or magic that works. Thus it was not uncommon for writers of this period to “cast magic and engineering in strikingly similar keys” [47, p. 64]. With such a conception of engineering, it made perfect sense to incorporate the fine arts, such as painting

[11] In this paper, we refer to the term ‘magic’ in its Renaissance meaning and context. However, we note that scholars have demonstrated how this remains relevant to contemporary engineering [48].

and drawing, and liberal arts. As an example of the latter, the Renaissance engineer and polymath Leon Battista Alberti combined “interests and methods characteristic of the engineering tradition with the linguistic and philological methods of the humanists” [47, p. 80] to make advances in cryptography.

By the late 20th and early 21st century, the capacity of engineers for vision-making and meaning-making came to receive more attention from historians dedicated to studying engineering on its own terms. Edwin T. Layton spotlighted the professionalization movement of 20th century American engineers and the shaping of their technocratic political ideology [49], [50]. Robert Post and Gene Ferguson emphasized the importance of imagery, memory, and emotion (e.g. enthusiasm) in understanding successful engineering projects and their public consequences [51], [52]. Rosalind Williams [26] produced a contemporary history of engineering centered upon her first-hand account of serving in an administrative leadership role at the Massachusetts Institute of Technology. Writing about engineering in its own terms, she depicted divergent political movements within the world of engineering (e.g. an “engineering science establishment”, “the Young Turks of design”, and “systems advocates” [26, p. 51]). Lastly, Matthew Wisnioski demonstrated how “engineers make their own context” [53] via his account of vision-making and contested political reform movements within the 1960s world of American engineering [4].

A vocabulary of change

It wasn’t until the 21st century that saw engineer-philosophers emerge to set down a coherent conceptual schema representing this embodied understanding of engineering. It revealed a conception of engineering couched in a vocabulary of change (Table 2). Here, the engineer is understood as someone “wants to change, to modify, or to convert the world represented by one state into a world represented by a different one” [54, p. 9]. It owed its expression to the written works[12] of a disparate group of engineers who saw the need to set down in writing what had until then been a largely unwritten, embodied understanding passed down in an unreliable tradition. They were supported by scholars sympathetic to the lived experience of engineering [55] and sensitive to the “hazardous” [56, p. 561] effects of the

[12] Key texts include the studies of engineering practice by James P. Trevelyan, Billy Vaughn Koen’s ‘Discussion of the Method’ (2003), Louis L. Bucciarelli’s ‘Designing Engineers’ (1994), Walter G. Vincenti’s ‘What Engineers Know and How They Know It’ (1990), and the collected writings of Samuel Florman, Henry Petroski, and Ove Arup.

broad-brushed use of the term ‘technology’ to represent novel aspects of our contemporary reality [57], [58], [59].

Table 2 The vocabulary of change: summary of key models and their shared conceptual schema

Key concepts	**Model of engineering and the world**	**Model of engineering practice**	**Model of engineering method**
Engineering	Engineering is a project of world-making [60], [61].	Engineering is a practice with a world of its own [62], [63].	Engineering is an act that makes a change in the world [54].
Engineer	Engineers envisage and enact political visions that seek a particular change in their world [53].	Engineers govern a world within which they can practice engineering [64], [65].	Engineers create piece-meal change in a particular situation in the world [54].
Change	Change is the outcome of a mutual shaping of engineering knowledge and social order [66].	Change is the outcome of reflective practice by engineers performed in real sites of practice [55].	A change in the world is set in motion by an engineering act [54].
World	"…a hybrid world in which there is no longer a clear boundary between autonomous, non-human nature and human-generated processes" [26]		
	Our world is shaped by engineering projects [67].	Our world is stabilized by routine engineering practices and performances [63].	Our world is constantly emerging by the engineering method of causing a change in the world.
Action	Action plays out on a world stage that does not distinguish between the human and natural world [24].		
	Engineers "simultaneously build artifacts and build environments in which those artifacts can function" [61, p. 65].	Engineering practice is sociotechnical and achieved through coordinated, communicative action [68].	"Know-what" (*phronesis*) is synthesized "know-why" (*episteme*), and "know-how" (*techne*) in an engineering act [69].
Judgement	Engineering judgement is applied to decisions of public importance in shaping the world [70].	Engineering judgement involves reflection-in-action because professional expertise requires responsiveness to context [55].	Engineering judgement is essential because of the ambiguity-by-definition of an engineering act.

Discussion: A Reconceptualization of the Engineer's Role

Thus far, we have set out on a historically and philosophically grounded path for reconceptualizing the engineer's role – from one of fabrication to action. To arrive at the latter, embodied understanding requires a turning inside out of the standard, technologically framed notion of engineering. Whereas the image of engineering as fabrication associates engineering with its *outcomes*, the idea of engineering as action requires an association of engineering with its *method.* However, the former image has such a strong hold, even among engineers:

> "Because the connection of the engineer with his completed design is so enduring and the connection with his use of method so fleeting, a person insists he is an engineer based on what he produces, irrespective of how he goes about it, instead of insisting that he is an engineer based on how he goes about it, irrespective of what he produces." [54, p. 8]

Thus, the two conceptualizations of the engineer's role presented here turn on the difference in emphasis between the two metaphors 'engineering produces technology' and 'engineering produces change'. The former emphasizes outcomes and the latter emphasizes method.

The path of reconceptualization also amounts to a turning inside-out of our perspective on the history and philosophy of engineering. In the standard perspective – the history of fabrication – the engineer's role is shaped externally by social and political elites. Their models of engineering perpetuate the image of a 'craftsman making artifacts' and order our understanding of engineering as pre-political and occurring within a self-regulating natural order. On the other hand, a marginal perspective – the history of action – expresses an internal conception of engineering – based on the experience of engineers – that is rooted in the etymology and visions of early *ingeniators.* In this view, engineers are not merely implementers of external goals but active, vital, and decisive leaders in visioning and shaping change in the world. Furthermore, engineering takes place not within a recurring natural order in which consequences are contained but rather an unknowable world in which consequences are unpredictable.

Importantly, the path for reconceptualizing the engineer's role set out in this paper is not an arbitrary definitional change for purely political purposes. By practicing conceptual history, we identified two stable, coherent, living conceptual lineages for representing the engineer's role. These are the ancient Greek lineage (*techne*) which centers fabrication (e.g. craft skills making useful artifacts) and the Latin lineage (*ingenium*) which centers action (e.g. ingenuity initiating a change in the world). They offer two distinct vocabularies for framing an engineering response to public crises: a vocabulary of technology (i.e. artifacts, nature, politics, thought, etc.) and a vocabulary of change (i.e. change, world, action, judgement, etc.). In the former, the central metaphor 'engineering produces technology' enables a normative framing in terms of responsibility (e.g. criteria, compliance, duty, responsiveness). In the latter, the central metaphor 'engineering produces change' enables a normative framing in terms of leadership (e.g. judgment, imagination, love of the world).

Our analysis suggests that the vocabulary of change could be more effective than the vocabulary of technology has been to date. Specifically, the former addresses the two failure modes we identify in this paper. Firstly, it addresses Mitcham's conclusion that the engineering profession requires a purpose or 'end' that is integral to it, rather than one that is externally imposed. By describing engineering as a form of human action, the vocabulary of change allows us to describe the purpose of engineering in terms of the purpose of human action, i.e. freedom. Thus, engineering is given an end (freedom) that is integral to it (action). Secondly, the vocabulary of change addresses the second failure mode located in Arendt's conclusion that a new conceptual vocabulary is required to represent the nature of engineering today. It does so by offering a philosophically coherent and empirically grounded conceptual schema (Table 2) that 'fits' the realities of engineering on its own terms.

Implications for Contemporary Projects of Engineering Reform

Our findings have had several implications for our own environmental engineering practice and projects of engineering reform. In adopting a vocabulary of change and centering an image of engineering as action, we have departed from the program of engineering literacy and framing of the engineer's role exemplified by the 'Engineering Education for Sustainable Development' movement. We will explain this departure in terms of three key aspects of our practice: what we know, what we do, and what it's all for.

What we know

As discussed at the outset, projects of engineering literacy are typically conceptualized by reformers as a means of educating engineers on their roles and responsibilities vis-à-vis public crises. In this manner, *The structural engineer's* *responsibility in this climate emergency* is intended to help engineers "get informed" by outlining "the role structural engineers can play in tackling climate change, by making informed design decisions and influencing other members of the project team"[20, p. 11]. We depart from this approach by conceptualizing engineering literacy as the ability to question the historical ideas and contexts that have defined what engineering is and what it can become. In this manner, we follow engineering educator and scholar of engineering Gary L. Downey in his "image of engineering as problem *definition* and solution" (own emphasis) [71, p. 435]. This has involved challenging received notions of what counts as engineering knowledge, to embrace the knowledge and methods that enable us to pose and answer such questions. To this end, we have sought to make space for a much broader conception of engineering knowledge in engineering research. We have done so by intentionally engaging with and integrating, and promoting useful yet unconventional epistemological frameworks, research methods, and bodies of knowledge, in conventional engineering spaces.

Our work amounts to a project of engineering literacy that enrolls engineers and those they work with in a shared understanding of the increasingly decisive role of engineering expertise in matters of public importance. We seek to highlight this in terms of the role of engineering standard setting in public-political decision making and support it with frameworks for public leadership based on historical and contemporary case studies. We also note that our renewed project of engineering literacy requires yet to be defined bodies of knowledge. In this sense, success in our work looks like a discernible, generational shift within research agendas. A shift from *reproducing* legacy bodies of engineering knowledge (e.g. certain branches of what is referred to as the engineering sciences or 'the fundamentals') to *introducing* new bodies of knowledge, with a strong grounding in new fundamentals. In our focus on engineering standards and research, we differ from the approach to engineering literacy centered upon engineering education [72].

What we do

We also depart from the standard approach of framing engineering responses to public crises in terms of a responsibility or obligation necessitated by the negative consequences of engineering work. *The structural engineer's responsibility in this climate emergency* exemplifies this framing, when it suggests that:

> “With such a large impact, it is clearly important that we all play our part in bringing global emissions down to the levels demanded by governments and the IPCC”[20, p. 10].

Instead, we find that meaningful and lasting transitions of engineering practice come from leadership, not compliance. We follow Stoddard et al. in working with said engineers to imagine and enact visions of plausible and desirable futures for their communities of practice [23]. In this work, we use the metaphor of ‘engineering produces change’ to position engineers as agents of change, instead of using the metaphor of ‘engineering produces technology’ to position engineers as implementers of requirements. We cast engineers and their professional bodies as leaders of transitions of engineering practice that meaningfully advance their practice in all its dimensions (e.g. economic, social, environmental). Specifically, we aim to cultivate an expectation and permission for engineering leadership and change within the relevant engineering communities whose practice contributes to climate change (e.g. structural, electrical, mechanical, agricultural engineering etc.). In this work, success will be measured in terms of the degree to which this reconceptualization of engineering literacy and the engineer’s role brings about meaningful engineering responses to public crises in actual sites of engineering practice.

What it’s all for

Lastly, our environmental engineering practice now involves actively questioning why engineers know what they know and do what they do in relation to the world at large. This departs from the standard approach to engineering literacy, which forecloses such questions by presenting ready-made solutions. For example, *The structural engineer’s responsibility in this climate emergency* is readily defined as “minimising our damage to the environment” by following “guidance on carbon footprint reduction”[20, p. 10]. We instead seek to cultivate reflexivity, understood as the capacity to rethink foundational concepts and assumptions in response to changing contexts. This involves critically engaging with the historical and philosophical roots of engineering using philosophical, sociological and historical methods – as we have sought to demonstrate in this paper. In this approach we are guided by the works of the Australian engineering educator Elizabeth Taylor [73]. She outlined the need for a subset of engineering scholars to study and debate the form of engineering (‘technosprudence’) for the same reason that a subset of legal scholars study and debate the form of the law (jurisprudence).

Conclusion: From Literacy for 'Responsibility' to Literacy for 'Leadership'

In this paper, we employed Hannah Arendt's [24] concept of 'fabrication' and 'action' to differentiate two lineages of engineering, each with a coherent and stable conceptual schema across time. Alongside the dominant schema rooted in the concept of '*techné*', our study surfaced a marginal schema rooted in the concept of '*ingenium*'. In the latter, engineers don't just *make things*, they *make history.* It affords a new vocabulary for engineering literacy, where engineers are understood to simultaneously *devise visions* about the kind of world we should live in and *devise actions* that bring about changes to realize that vision. Thus, while acknowledging that engineers have and will continue to be defined in terms of their role in supervising or participating in the making of things, we demonstrated an embodied understanding of engineering in which making was never an end in itself, but rather a means to the end of a shared vision of how the world should be.

While acknowledging the validity of both perspectives – i.e. 'engineering produces technology' and 'engineering produces change' – we proposed that, when these conceptions of engineering are employed as a metaphor and normative device in response to real-world public crises, the latter may prove to be more effective than the former in delivering a meaningful, imaginative, and fully realized response. On the other hand, if we continue to rely on the narrow definition of engineering vis-à-vis technology, we will be handicapped by a vocabulary and conceptual schema that limits the agency and reflexivity of engineers. This hinders their ability to perform the role of making history which they are called upon to do in moments of public crises. A reconceptualization of the engineer's role, from fabrication to action, can underpin a different understanding of engineering literacy. Namely, as the capacity to engage with the history of engineering to question received notions of the engineer's role. This renewed project of engineering literacy has the potential to enable more meaningful engineering responses to public crises.

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