The Logic of Ingenuity

Part 1: Engineering Design

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The process of (abductively) creating a diagrammatic representation of a problem and its proposed solution, and then (deductively) working out the necessary consequences, such that this serves as an adequate substitute for (inductively) evaluating the actual situation.

This article is the first of a four-part series, the title of which is a bit counterintuitive and perhaps even slightly misleading. Common parlance tends to identify logic with strictly deductive reasoning and ingenuity with cleverness, so the reader might be expecting me to offer a procedural algorithm that somehow guarantees an innovative outcome ("The Rationality of Practice," September 2012). What I have in mind instead is logic in the broader sense as the norms of thought in general, and ingenuity in the narrower sense as the distinctive essence of engineering practice; after all, "ingenuity" and "engineering" have the same etymological roots ("Philosophy and Engineering," September 2008).

If the phrase sounds vaguely familiar, that may be because I used it in my last philosophical InFocus column ("Representation and Reality," September 2015). I suggested there that the "logic of inquiry" identified by Charles Sanders Peirce as integral to science – which consists of formulating a hypothesis (abduction), explicating what follows from it (deduction), and then trying to falsify it (induction) – also serves as a "logic of ingenuity" in engineering. My goal in these follow-up pieces is to explore such a notion more fully. By doing so, I hope both to complement and to supplement what William M. Bulleit has recently written in this magazine about "The Engineering Way of Thinking" (Structural Forum, December 2015 – March 2016).

Although they are structurally analogous, scientific and engineering reasoning are widely understood as pursuing very different ends ("The Principle of Insufficient Reason," May 2008). Rather than the *discovery* of a universal theory with general application, an engineer is typically oriented toward the *design* of a particular artifact for a specific purpose. As I have said many times before, much like science is viewed as an especially systematic way of *knowing*, engineering may be viewed as an especially systematic way of *willing* ("Engineering as Willing," March 2010).

The "abductive" aspect of engineering design is imaginatively conceiving a potential artifact. Peirce noted that humans are remarkably successful at "guessing" scientific hypotheses, and argued that this reflects how our instincts and sentiments are attuned to nature through calibration over many generations. Likewise, by gaining extensive experience of the right kind, an engineer cultivates a disposition to perceive the key attributes that are likely to make something suitable for its intended function ("The Nature of Competence," March 2012).

The "deductive" aspect of engineering design is carefully translating those characteristics of the proposed artifact into its physical requirements ("Artifacts and Functions," September 2010). Some engineers are "hands-on" enough to fashion their own contrivances, but most instead have to explain them in detail – for example, by preparing drawings and specifications – so that someone else will be able to assemble them.

The "inductive" aspect of engineering design is rigorously testing the artifact once it actually exists, in order to confirm that it performs as expected. This is fairly routine when it is feasible to manufacture prototypes, as for most engineered *products*; but it is rarely practicable for large engineered *projects*, such as buildings and bridges.

In these cases, a second cycle of abduction-deduction-induction must be nested between the first two steps just outlined: engineering *analysis*. The "abductive" aspect is developing an idealized model of the artifact and its immediate environment ("Complicated + Complex = Wicked," July 2015). The "deductive" aspect is processing this model in accordance with idealized assumptions; today, this is often done with the help of a computer. The "inductive" aspect is interpreting the results by comparing them with idealized rules, which are usually prescribed by industry-wide codes and standards.

Peirce pointed out that the logic of inquiry in science is ordinarily self-correcting in the long run; the world will confront a persistent investigator with unpleasant surprises if a hypothesis is inconsistent with how it really operates. Unfortunately, when this happens in engineering, there tends to be a high cost – measured in dollars and/or in lives ("Remember the Hyatt," January 2011). To avoid this, the logic of ingenuity involves the assessment of the model, rather than the artifact itself. Engineering science, including forensics ("Learning from Failures," July 2006), provides genuinely inductive support for the overall validity of this approach by supplying and verifying the various *heuristics* that engineers implement in executing it ("The Engineering Method," March 2006; "Heuristics and Judgment," May 2006).

If the conclusion of the analysis is not acceptable, then it is necessary to revise the model – or possibly even the artifact concept – and carry out another analysis; the engineer must deem everything to be satisfactory before moving on to drafting instructions for constructing the artifact itself. Thus, *representation* is at the heart of what William Addis called a "design procedure" – most notably in non-prototypical engineering, where it is essential to achieving both outputs: description and justification ("The Nature of Theory and Design," May 2009). I will close for now by calling attention to a couple of additional features of the latter task.

First, Peirce strongly believed that all deductive reasoning is, in an important sense, mathematical; and all mathematical reasoning is *diagrammatic*. What he meant by this is that it proceeds by creating, manipulating, and observing an *icon* that accurately reflects the *form* of the significant *relations* among the parts of the object of interest. Hardy Cross hinted at this facet of engineering analysis when – as recounted by one of his last students at Yale University, Edward O. Pfrang – he defined a structure as "a system of connections loosely held together by members," rather than the other way around.

Second, it is crucial for the engineer – by exercising good practical judgment – to discern which relations are truly significant, and then devise a suitable icon of their form accordingly. Mete Sozen expressed a similar concern by posing a question that is well worth pondering: "Is an exact analysis of the approximate model an approximate analysis of the exact structure?" An affirmative answer is a fundamental, yet subtle – and therefore easily overlooked – presupposition of modern engineering.

I will have more to say about these two points in subsequent installments.▪

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