The Logic of Ingenuity

Part 3: Engineering Reasoning

By Jon A. Schmidt, P.E., SECB

The thesis of this series is that *engineering* reasoning is a practical implementation of what Charles Sanders Peirce described as *diagrammatic* reasoning. Most people associate the word "diagram" with a picture of some sort, but he viewed it primarily as "a concrete, but possibly changing, mental image of such a thing as it represents. A drawing or model may be employed to aid the imagination; but the essential thing to be performed is the act of imagining" (NEM 4.219n1; 1906). Here is his technical definition:

> *A* diagram *is a representamen which is predominantly an icon of relations and is aided to be so by conventions. Indices are also more or less used. It should be carried out upon a perfectly consistent system of representation, founded upon a simple and easily intelligible basic idea (CP 4.418; 1903).*

Peirce's terminology here may require some explanation. A *representamen* (pronounced "rep-re-sen-TAY-men") is what he alternatively called a *sign*: "something which stands to somebody for something in some respect or capacity" (CP 2.228; 1897). "All thought being performed by means of signs, logic may be regarded as the science of the general laws of signs" (CP 1.191, EP 2.260; 1903) – i.e., *semeiotic* – which classifies them by, among other things, how they represent their objects: *icons* (e.g., statues) do so "only in so far as they resemble them in themselves"; *indices* (e.g., weathervanes) do so "only by virtue of real connections with them"; and *symbols* (e.g., sentences) do so "because dispositions or factitious habits of their interpreters [i.e., conventions] insure their being so understood" (EP 2.461; 1911).

Peirce further subdivided icons into *images*, "which partake the simple qualities"; *diagrams*, "which represent the relations … of the parts of one thing by analogous relations in their own parts"; and *metaphors*, "which represent the representative character of a representamen by representing a parallelism in something else" (CP 2.277, EP 2.274; 1903). Because diagrams embody formal *relations*, they need not always do so visually; although geometric figures are obvious examples, algebraic expressions also qualify. A free-body sketch and the associated equations of static equilibrium *both* reflect the relations among the forces that are acting upon and within a structural element.

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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.

Indices in a diagram point to its *reference*, the actual relations that it represents. Conventions help convey its *signification*, the new information that emerges from manipulation of it in a manner that complies with the explicit or implicit rules of "a particular system of symbols – a perfectly regular and very limited kind of language" (CP 2.599; 1902) – such as a collection of postulates and axioms, or a stipulated notation. The principles of mechanics serve this function for *deriving* the proper equilibrium equations from a free-body sketch – which typically includes depictions such as lines for members, vector arrows for forces, and triangles for supports – and *solving* them subsequently reveals what are designated as the reactions, shears, and moments due to an applied load.

This is what makes diagrammatic (and engineering) reasoning so powerful. Although it constitutes deductive inference – there is nothing in the conclusion that was not already embedded somehow in the premises – it still brings to light something that was not initially evident:

> *… deduction consists in constructing an icon or diagram the relations of whose parts shall present a complete analogy with those of the parts of the object of reasoning, of experimenting upon this image in the imagination, and of observing the result so as to discover unnoticed and hidden relations among the parts (CP 3.363, EP 1.227; 1885).*

It is important to keep in mind that the diagram itself and the representational system that governs it are each *provisional*. They inevitably include abstractions and idealizations, which are *selected* by the person who engages in this type of reasoning – which thus involves *creativity*, because it is active, not purely passive: "Thinking in general terms is not enough. It is necessary that something should be DONE. In geometry, subsidiary lines are drawn. In algebra permissible transformations are made" (CP 4.233; 1902).

Note again that not just *any* modifications are allowed; rather than being completely arbitrary, they must conform to the precepts of the chosen representational system, which also then dictate their outcomes. As Peirce wrote elsewhere: "… all reasonings turn upon the idea that if one exerts certain kinds of volition, one will undergo, in return, certain compulsory perceptions … certain lines of conduct will entail certain kinds of inevitable experiences" (CP 5.9; 1905). Nature corroborates or falsifies a theory through such encounters in the actual world, but how does a *hypothetical* one possess a similarly normative aspect?

> *Now, sometimes in one way, sometimes in another… certain modes of transformation of Diagrams… have become recognized as permissible. Very likely the recognition descends from some former Induction, remarkably strong owing to the cheapness of mere mental experimentation. Some circumstance connected with the purpose which first prompted the construction of the diagram contributes to the determination of the permissible transformation that actually gets performed (NEM 4.318; 1906).*

In other words, which moves are legitimate becomes apparent mainly through the persistent activity of the intellect – which is far less costly or time-consuming than a genuinely inductive investigation, because "it does not deal with a course of experience, but with whether or not a certain state of things can be imagined" (CP 2.778; 1902). How one proceeds in an individual case, subject to such constraints, depends on one's *intention*; the entire train of thought – i.e., the sequence of signs – has to incorporate the features that are relevant to achieving that end, while other considerations are largely ignored. This exercise of judgment guides the configuration of not only the diagram itself but also the representational system.

For modeling the behavior of something material, an acceptable degree of approximation is more likely when these have been developed, tested, and refined through rigorous inquiry. This is what ultimately enables the simulation of *contingent* events with *necessary* reasoning: "Such operations upon diagrams, whether external or imaginary, take the place of the experiments upon real things that one performs in chemical and physical research" (CP 4.530, 1905). There is no such thing as a frictionless pin, but engineering *science* has demonstrated that treating standard shear connections at the supports of a steel beam *as if* they provide no rotational restraint whatsoever facilitates a valid assessment of the member's strength and serviceability.

The bottom line is that diagrams and representational systems are *artifacts* that people *design*, so it should not be surprising that engineers routinely employ them. As summarized by Michael H. G. Hoffmann, a philosophy professor at Georgia Tech, in a working paper entitled "Seeing Problems, Seeing Solutions: Abduction and Diagrammatic Reasoning in a Theory of Scientific Discovery" (**https://smartech.gatech.edu/bitstream/handle/1853/24031/wp15.pdf**, emphasis in original): "… *seeing a solution* presupposes *seeing a problem* … The central idea of this kind of reasoning is that we *see* problems when we try to represent what we know about something … We have to *represent* what we know – or think to know – in order to *see*, first, its limitations and, second, new possibilities."

This hints at broader applications, even outside the realm of engineering, which will be the subject of my concluding article.▪

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References

In accordance with standard scholarly conventions, Peirce's works are cited as follows, along with the year when he authored the quoted text. CP with volume and paragraph number is *The Collected Papers of Charles Sanders Peirce*, edited by Charles Hartshorne, Paul Weiss, and Arthur W. Burks, published by Harvard University Press in 1931-1935 and 1958. EP with volume and page number is *The Essential Peirce*, edited by Nathan Houser, Christian Kloesel, and *The Peirce Edition Project*, published by Indiana University Press in 1992 and 1998. NEM with volume and page number is *The New Elements of Mathematics*, edited by Carolyn Eisele, published by Mouton & Co. in 1976.