From the Historical Continuity of the Engineering Imaginary to an Anti-Essentialist Conception of the Mechanical-Electrical Relationship

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Introduction

Accumulated work by historians and philosophers of science allows us to know details on how metaphor, analogy and modeling (some would add allegory and mimesis) become constitutional elements of the scientific phenomenon. I am interested here in something much less studied, namely, the place of the same elements in technology. In respect to technology, the literature is scattered and focused only on the history and philosophy of engineering models. The place of the rest of the aforementioned elements in technology – not to mention the interrelationship of metaphors, analogies, and models – remains, to my knowledge, an unexplored territory, especially for historians of technology. I will try taking a step into that territory by introducing a sample from the history of engineering analogies (Philosophers and historians of science have argued that starting from analogies may be justified by the fact that analogies are components of both metaphors and models). The first suggestion of the history of this chapter is then that analogies have been an indispensable component of not only science, but also technology.[1]

1 For an early and a more recent survey of the metaphor, model and analogy relationship in science, see Leatherdale 1974, Bailer-Jones 2002. For recent collections of essays on models, mostly scientific, see Morgan and Morrison 1999, Klein 2001, Chadarevian and Hopwood 2004. For case studies devoted to the history of engineering models, all concerning mechanical models, see Smith 1976-1977, Harley 1991-1992, Kooi 1998,

My work starts with analogies between two of the exemplar machines of eighteenth and nineteenth century capitalism, the steam engine and the dynamo. It begins with the period when the electric lighting distribution lines were first introduced. It concludes with analogies from the period when long and interconnected lines of electric power transmission had become the rule, alongside a transition from mechanical-electrical to electrical-mechanical analogies. The flow of the calculating analogy always went from the standard to the novel phenomena, which means that it was not the nature of the phenomena – mechanical or electrical – that determined the flow of the analogy. A phenomenon was more standard – and, as such, more natural – after it had become relatively familiar by the availability of a standard, mass-produced, artificial circuit that embodied it. Based on the continuities that we find in this transition, I move on to also suggest that the difference between the mechanical and the electrical are socially constructed. More specifically, I suggest that the mechanical and the electrical have been products of the expanded reproduction of a certain mode of producing nature socially, not two ontologically different states of nature.

This suggestion points to the configuration and reconfiguration of metaphors, models and analogies as normative rather than descriptive processes, interpretations of nature rather than representations of it. Following this, I further suggest that the production and use of analogies was an integral element of calculation. Indeed, the analogies that I introduce over the course of the following pages were produced and used in the context of calculating the stability of increasingly longer and interconnected electric lines. Between the 1880s, when my narrative starts, and the 1940s, when it ends, the concept 'analog' computer emerged, in interaction to a transition from mechanical-electrical to electrical-mechanical computing analogies. In this sense, the story of this chapter also involves the computer, the exemplar machine of twentieth century capitalism.

Mechanical-Electrical to Electrical Mechanical Calculating Analogies

In the 1880s, it was clear to engineers that an electrical phenomenon was not ontologically different from a mechanical phenomenon, but an expanded reproduction of it, based on the same pattern of accumulation of labor power. In the words of H. Franklin Watts, who looked at the elec-

Wright 1992. For a sample of studies devoted to the philosophy of technical analogies, see Kroes 1989, Sarlemijn and Kroes 1989.

trical from the viewpoint of the mechanical, the two differed only in the "mechanical skill" embodied in them. "It is true saying and worthy of all acceptation," stated Watts in his first of his 1887-1888 series of articles on "Practical Analogies between Mechanical and Electrical Engineering," "that an electrical engineer is about eight-tenths mechanical and two-tenths electrical." His introductory example successfully supported this argument. For Watts, "electrical knowledge" and "mechanical skill" were inseparable. He argued so by referring to the construction of a dynamo armature: to be properly balanced, so as to avoid both the electrical phenomenon "eddy" or "Foucault" currents (which increased with a bulkier supporting mechanical structure) and the mechanical phenomenon of a weak supporting structure an engineer needed both ("electrical knowledge" and "mechanical skill") (Watts 1887: 246).

With his following example, Watts elaborated on how an electrical machine was also a mechanical machine. For his comparison, he chose the machines that exemplified mechanical and electrical engineering: the representative of electrical engineering was the dynamo (which was structured around the armature); the representative of mechanical engineering was the steam engine. Watts introduced the analogy between the two by claiming that a steam engine resembles a dynamo "not only in its mechanical construction and attention necessary to operate, but also in the calculations of the theoretical performance." He acknowledged that the steam engine and the dynamo seemingly "differ greatly," as they appear to rely on reverse processes, since with a steam engine the energy of an invisible fluid is converted to visible mechanical motion whereas with the dynamo a visible mechanical motion is converted to an energy of an invisible fluid. But, by turning to history, Watts argued that there was no difference at all because the operation of both machines was actually reversible: the first steam engine, explained Watts, was used as a pumping engine. Similarly, the function of dynamo was the reverse of that of the motor. Accordingly, at this point Watts re-introduced to James Watt and Michael Faraday as inventors of machines that exemplified the same pattern (Watts 1887: 246).

For Watts, the calculations of mechanical and electrical machines were analogous. The intervening accumulation of "mechanical skill" had not changed its pattern. "The weak point of a [steam] engine," wrote Watts in the first line of his second article of the series, "may be said to be its crank-bearing, the fiction of which increases with the horse-power produced by a single crank." As we moved to horsepower of 1,000 and higher, the "lubrication of the crank becomes a very important element." "The weak point of the dynamo," added Watts, "is its commutator, the friction of which, while not necessarily increasing with the *output* of the dynamo, increases with the current to be collected." Watts was of the opinion that the difficulties with the crank, as compared to those with the commutator, were "in about the ratio of six of one to half a dozen on the other" (Watts 1887: 258).

Some of the details of the "practical analogies" between mechanical and electrical engineering of Watts displeased Rudolph M. Hunter, a mechanical engineer. In early 1888, Hunter and Watts exchanged a series of letters on the issue of practical mechanical-electrical analogies through the pages of the *Electrical World* (Hunter 1888). They were neither the only, nor the last ones to do so. When John Waddell, who was with the Royal Military College of Canada at Kingston, Ohio, published an article in order to argue that the difference of electrical potential was analogous to the pressure difference of the air, he drew the protesting response of A. W. K. Peirce. For his analogy, Watts had used standard machines. By contrast, Waddell described an analogy between the generation of electric potential in a conductor moving across a magnetic field and an air box with an "indefinitely large number of little paddles." The mechanical field in which the air box was moved was provided by two boards, which represented magnetic poles, and steel wires, which represented magnetic lines. The purpose of the analogy was to assist in computing savings in copper in dynamo (or motor) design. Peirce found this analogy "imperfect," arguing that when no current was flowing in the conductor none of the energy required to move the conductor in a magnetic field could be charged to the generation of electrical potential – the current being zero, the work would be zero at the conductor when moved in a magnetic field. During the move of the airbox in the mechanical field there was production of heat in the box. Waddell replied with a complex thought experiment – a test which he was "not in a position to make" – in order to argue that in a new machine, of which the transformer was an exemplar, heat could be developed in the secondary circuit even if it was open. I understand this debate to reveal that structural asymmetries that did not matter from a mechanical viewpoint but could become important when considered from an electrical perspective (Waddell 1894; Peirce 1894).

To be sure, the use of mechanical-electrical analogies did not start with the electric network of lighting and power. In the year 1887, on the same day when Watts started publishing his series of articles on general mechanical-electrical computing analogies in the pages of the *Electrical World*, the *Electrical Review* hosted an article on a mechanical-electrical computing analogy written by Arthur Kennelly. Watts stayed at the general level because he wrote in reference to the relatively new electric networks of lighting and power. Kennelly was, however, more specific because he wrote about the relatively old electric networks of telegraphy. As a result, unlike Watt's article, Kennelly's – entitled "On the Analogy between the Composition of Derivation in a Telegraph Circuit into a Resultant Fault, and the Composition of Gravitation on the Particles of a Rigid Body into a Center of Gravity" – included the formalization of the calculating analogy into a calculating equation (Kennelly 1887).

Mechanical-electrical analogies were central in pioneering alternating current treatises. For example, in their 1893 influential handbook on the analytical and graphical computation of alternating currents, Frederick Bedell and A. C. Crehore included an appendix on mechanical-electrical analogies (Bedell and Crehore 1893). The mechanical-electrical computing analogy between the steam engine and the dynamo machine remained fixed to the electrical engineering unconscious, to erupt in times of crisis. For example, worried about the profitable but tremendously risky acceleration of the lengthening of alternating current transmission lines, Harold W. Buck protested against those who legitimized such acceleration by advancing calculations that overplayed the profits and downplayed the risks. During a 1923 AIEE Conference paper discussion, he protested by employing an elaboration of the steam engine analogy. Given the intervening increase of transmission length, he quite properly adjusted this analogy to the perspective of the transmission component (as opposed to generation component, see Watts) of the process of the production of electric power:

> The transmission of power from a piston for instance to a flying wheel through a connecting rod is a very simple proposition, but when the connecting rod is lengthened out to such a distance that its inertia and elasticity become factors which cannot be controlled then some other method must be found. A transmission line is merely a connecting rod and in the very high-voltage lines of great length the inertia and elasticity are becoming difficult factors to handle and the papers under discussion prove it (Dellenbaugh 1923: 822).

The gradual change from mechanical-electrical to electrical-mechanical computing analogies came along the change from analogies between phenomena to analogies between circuits. Compared to the relationship between mechanical and electrical phenomena, the relationship between mechanical and electrical circuits better supported an essentialist split between the mechanical and the electrical. The two equivalent circuits appeared to be related by an analogy between two natures that were, nevertheless, different. Mediating between the electrical-mechanical circuit analogy was a mathematical function, which described both circuits.

This prepared for the completion of the conceptual transition from analogies and models to analog computers.

We can elaborate on this transition by considering a mechanical model that circulated widely among the community of electrical engineers. In 1926, S. B. Griscom, General Engineer at Westinghouse, described what he called a "mechanical analogy" to the problem of electric transmission stability (Griscom 1926). He would not refer to it as a mechanical model, and he could not, as E. W. Kimbark in 1948, refer to it as a "mechanical analogue." Kimbark, who was at the Electrical Engineering Department at Northwestern University, spoke about this model at an American Power Conference (Kimbark 1948). When Griscom was writing in 1926 amidst the peak of electrification, he avoided the concept model because it signified a past state-of-the-art computing technology. Instead, at the cost of being too general, he baptized his computing artifact a "mechanical analogy." Kimbark had a new concept that Griscom was lacking, and he could now be specific without having to resort to the term "mechanical model," which pointed to the past. His term – "mechanical analogue" – pointed to the future. For him in 1948, Griscom's 1926 "mechanical analogy" was a "material analogue." We are just a step before the concept analog computer. In the rest of his paper, Kimbark considered elaborate versions of Griscom's "mechanical analogue," appropriate for extending the study of stability to more complex networks and transient load conditions.

A detailed description of the same mechanical model was given by L. F. Woodruff in his academic textbook on transmission and by Robert D. Evans in an influential industrial textbook that was published by some Westinghouse engineers. It consisted of two rotatable units mounted on a common shaft and provided with lever arms that were connected at the outer ends by a spring. The one rotatable element was an analog of the generator and the other of the motor. Both elements were provided with means for applying torque in such a way as to stretch the spring connecting the level arms. The radial distance from pivot to any point on the spring was analogous to the line voltage at corresponding point, the length of the spring to the line reactance drop, the tension of the spring (proportional to its length) to the line current, the torque of either arm (product of the length of the arm and component of spring tension perpendicular to arm) to the active power, the product of the length of the arm and component of spring tension along the radius at any point to the reactive power, and the angle between any two points in the spring to the phase displacement at the corresponding points of the system. This mechanical model was suitable to demonstrate changes in movement that were significant from the standpoint of stability. It was proportioned so as to model both steady and transient state conditions. By addition of rotatable elements and springs, it could be extended to model complicated networks (Woodruff 1938: 181-182; Central Station Engineers of the Westinghouse and Manufacturing Company 1944).

From Evans we learn that the electrical engineers who used it still commonly called it a "mechanical model." In 1948, Kimbark would use a new concept by calling it a "mechanical analogue." The difference in the concepts used by Griscom in 1926 ("mechanical analogy") and by Kimbark in 1948 ("mechanical analogue") for the same computing artifact is suggestive about the conceptual change between the two different sub-periods of the computation-electrification relationship. Reading Griscom's 1926 article leaves us to wonder whether he had devised something material. Griscom included only a sketch of his "material analogy." It is only after reading the contribution of Evans to the influential Westinghouse electrical engineering textbook, where we see a published picture of a man holding it, that we understand that we have to do with a mechanical model. Evans provided two figures of it. Under the first, which was a picture of a man setting the devise in order to compute a certain transmission scenario, he wrote "The mechanical model." Under the second, which was a sketch of it placed next to its corresponding vector diagram and the equations that described it, he wrote "The mechanical analogy for power system stability." Evans clarified that the "mechanical analogy" could be useful even when a "mechanical model" was unavailable (Central Station Engineers of the Westinghouse and Manufacturing Company 1944).

The conceptual transition that I just outlined interacted with the shift from mechanical-electrical to electrical-mechanical analogies and the associated shift from analogies between phenomena to analogies between circuits described by the same form (the same mathematical equation). We can take a mid-point example, which show that during the second sub-period, some electrical phenomena were standardized enough to provide the analogy for non-standard mechanical phenomena. The 1931 *AIEE Transactions* hosted an article entitled "An Electric Analog of Friction: For Solution of Mechanical Systems Such as the Torsional-Vibration Damper," written by H. H. Skilling who was at Stanford University. This was no longer a paper on a mechanical-electrical analogy. It was one on an electrical-mechanical (electromechanical) analogy (Skilling 1931).

In his 1941 review article, labeled "Electrical and Mechanical Analogies," W. P. Mason started with a section entitled "Early borrowings of electrical from mechanical theory" to conclude with a section entitled "Borrowings of mechanical theory from electrical network theory" (Mason 1941). Two years later, in another review article, John Miles, who was at the California Institute of Technology reviewed an associated conceptual change. During the transition from mechanical-electrical to electrical-mechanical analogies, the electrical analogy itself was split into two in order to best adjust to the new calculating purposes: an older electromechanical analogy was conceptualized as the "direct method," and a newer one as the "inverse method" or the "mobility method" – the term "mobility" emphasized the relative flexibility of the new method. Miles also called them the "electrostatic" and the "electrodynamic" analogy (Miles 1943, 183-192).

Convinced about the superiority of the new electromechanical analogy, Miles tried to explain it:

> The fundamental imperfection of the old electrostatic analogy of velocity *across* mechanical elements being represented by current *through* electrical elements and force *through* mechanical elements being represented by voltage *across* electrical elements causes little trouble in simple systems; but it may also be said that the direct solution of these systems, sans analogies, gives even less trouble. In the case of a somewhat more complicated system, however, the newly initiated user of the old electrostatic analogy is very likely to become hopelessly confused and arrive at the most erroneous answers (Miles 1943: 184-185).

How can we understand what the advantage of the new method was so as to move on to appreciate Miles' introductory statement, according to which "the choice of analogy to be used is usually one of convenience, but that certain systems intrinsically make only one analogy possible." At first, Miles' article reads more like a confirmation of the first half of this statement than as proof of the second half. As I see it, the difference had to do with the fact that the new "electrodynamic analogy" was better for visualizing a calculation path that went from an electrical to a mechanical network whereas the old "electrostatic analogy" was better for computing the other way around. Since, by late 1940s, the dominant direction of calculations was from the electrical to the mechanical, the electrodynamic version of the analogy was becoming superior (Miles 1943: 183).

This inversion became possible by the availability of standard, relatively inexpensive electrical components. More standard electrical components meant that it was now relatively easier to construct a standard electric circuit and then use it to compute an unknown mechanical circuit. This is precisely what Gilbert D. McCann and H. E. Criner were introducing in a series of articles on calculating analogies between electrical and mechanical circuits during the second half of the 1940s. In one of these articles, McCann and Criner included a three-table figure similar to one that Miles had included in his article. The middle table included the elements of a mechanical system. The left and the right table included elements of an electrical system. The tables were similar but their titles were different. Miles labeled the left and the right table "electrostatic" and "electrodynamic" analogy perspectively; McCann and Criner "electric" and "electrical." "Physical mechanical elements," wrote McCann and Criner underneath their figure, "can be represented by either one of two analogous electrical systems." First, what was consciously noted by this sentence, was that mechanical systems were being represented by electrical (the inverse was, by then, meaningless). Second, consciously or not, through their choice of concepts, McCann and Criner had blocked the older electromechanical analogy: an analogy between elements of circuits cannot be electric-mechanical, it can only be electrical-mechanical. In other words, during the inversion from mechanical-electrical to electromechanical computing analogies, one version of the (electromechanical) computing analogy was aborted – there was not then a simple inversion, but also, a specification of the computing analogy (McCann/Criner 1945: 138).

To be sure, the concept 'model,' as we understand it, was used only for mechanical models. "The electrical-analogy method," argued McCan and Criner, "has several distinct and important advantages over the use of models or existing mechanical calculators. It is relatively inexpensive to build suitable elements to represent a wide range of other physical constants. These can readily be put in a form suitable for quick connection to represent a wide range of physical systems." In other words, the world was electrified enough so that an analogy could flow from the phenomena of a standardized electrical world to nature in order to allow the consideration of an electrified version of the nature as natural (McCann and Criner 1945, 138).

In 1887, Watts thought of the dynamo as analogous to the steam engine. He used the old exemplar of a mechanical machine (steam engine) as a model of the new exemplar of an electrical machine (dynamo). After the 1940s, the flow of this general analogy was also reversed. For example, MIT's D. C. White and A. Kusko wrote that they had developed a laboratory machine which "effectively demonstrates and supports the approach and indicates the common root that all machines basically have in a cylindrical structure with prescribed surface winding patterns." The title of their paper was "A Unified Approach to the Teaching of Electromechanical Energy Conversion." In early electrification, the unifying machine model was mechanical. By late electrification, it had become electrical. To no one's surprise, the classic engineering textbooks on analogies of the post-World War II period were about electromechanical analogies, not mechanical-electrical analogies (White/Kusko 1956: 1033).[2]

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2 For classic handbooks on engineering analogies from the 1940s, see Olson 1943, Johnson 1944, Trimmer 1950.

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