The cognitive work of metaphor and analogy in scientific practice

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Abstract: in this paper I consider how contemporary research from cognitive science and philosophy of science reinforce and can be used to articulate further Mary Hesse's project of a "family resemblance research program" for analyzing scientific change. After briefly discussing Hesse's insights about the metaphorical nature of scientific language, the analysis shifts the discussion to the current philosophical focus on models and on scientific practices, rather than language. Using cases drawn from historical and ethnographic research on scientific practices, I argue for the centrality of a family resemblance notion for capturing the dynamics of concept representation and of analogy for model-based reasoning processes in concept formation and problem solving more broadly.

Keywords: concept formation; analogy; family resemblance; models.

1. *Introduction*

Models have pride of place in contemporary philosophy of science – a situation that would have been inconceivable when Mary Hesse started writing on models, analogies, and metaphors. That was the heyday of logical positivism and hers were pioneering views. Still, despite today's emphasis on models, their fundamentally analogical nature – and thus the need for a theory of analogy – is not widely recognized in philosophy of science. Although I drew inspiration from her book *Models and Analogies is Science* (Hesse 1963) when I began my own research on what I later came to call "model-based reasoning", in revisiting Hesse's writings on models, metaphors, and analogies from 1952 (Hesse 1952) through to the two, related, 1988 articles (Hesse 1988a; 1988b) for writing this article I have come to realize that since her earliest published work the analogical basis of scientific theories has been one of two abiding themes in Hesse's philosophical career; the other being the relation between religion and science. Although my focus here is on the former, it bears pointing out that the two themes are interrelated in her philosophy. For Hesse, if the language through which both science and religion describe and explain the unobservable is "the language or metaphor and symbol" (Arbib and Hesse

philinq III, 1-2015, pp. 133-156
ISSN (print) 2281-8618-ETS

1986: 181) then they are not the disparate modes of knowing analytic philosophy has deemed them to be.

Hesse's later work made use of research in the cognitive sciences to further her ideas about the "family resemblance" structure of scientific concepts and the role of metaphor and analogy in scientific thinking. As with her contemporaries, Hesse's focus remained on the language of science. Contemporary philosophy of science is largely concerned with the representational and inferential practices of scientists. A "cognitive-historical" method (Nersessian 1987; 1995; 2008) has been the point of departure for my own research on the processes of concept formation and change in science. The cognitive-historical method places the cognitive practices of scientists on a continuum with human representational and reasoning practices involved in solving more ordinary problems, and, reflexively, raises considerations stemming from the cognitive practices of scientists that cognitive research is not yet adequate to explain. In this paper I discuss Hesse's contributions and insights with respect to the meaning-making practices of scientists and the cognitive work of metaphor and analogy in model-based reasoning.

Metaphor and analogy are difficult to distinguish precisely. While not articulated explicitly I read Hesse as making an implicit distinction: Although reasoning processes underlie both metaphor and analogy, Hesse relates metaphor to the meaning-giving aspects of analogy and analogy to a form of reasoning underlying metaphors and models she calls "inductive", which is better called "abductive". I will use this rough distinction to structure my discussion since it enables bringing contemporary insights from cognitive science and philosophy of science to bear on her call for a "family resemblance research program" two components of which are the "family resemblance character of concepts and consequent analogical nature of inference" (Hesse 1988b: 337-338).

2. *The family resemblance character of concepts*

Hesse explicated her insights about the metaphorical nature of scientific language and the post-positivist problems of "meaning change" and "incommensurability" in terms of the notion of "family resemblance", first as discussed by Wittgenstein and then in relation to cognitive science research on the nature of human categorization. In a line of experimental research begun by Eleanor Rosch and her colleagues (see, e.g., Rosch 1975; 1987; Rosch and Lloyd 1978; Rosch and Mervis 1975), human categorization practices were shown as not in line with the classical essentialist view of concept representation as by means of "necessary and sufficient conditions". Rather, the experimental research supported the notion that something is categorized as an instance of "X" based on its resemblance to a central prototype, and thus the representation of a concept is best characterized as a set of family resemblances with specific instances varying with respect to the features they share. To take a simple example, something would be characterized as a bird based on features it shares with a typical bird, e.g. a robin. On such an account, a blue jay would be more immediately categorized as a bird than a penguin. Further, accidental features play a significant role in the process. For example, a flying creature is usually categorized as a "bird", but "flies" is an accidental feature of "bird" since not all birds fly. Hesse saw this cognitive research as having significant implications for the post-positivist problems surrounding "meaning change" and also as providing a basis of support for her long held views on the metaphorical nature of scientific language. Her last work on the subject calls for "case histories of concept formation in scientific theory-change analyzed from a family resemblance point of view" (Hesse 1988b: 337), which has since been answered with numerous cases of conceptual change.[1] Indeed, contemporary accounts stemming from discussions of the pros and cons of family-resemblance-based analyses of categorization concept formation in cognitive science, including "schemata", "dynamic frames", and "idealized cognitive models", have proven quite fruitful for addressing the post-positivist problems and for analyzing the dynamics of conceptual change. These dynamics can be more readily described and explained by appreciating that concept formation in science is a process of *construction* – often with contributions spanning the work of several researchers – in which different instances of a concept are related through a family resemblance structure.

As noted, there is now a substantial body of case histories exploiting this "point of view", and I will use my research on the formation of the concept of field as a fitting exemplar.[2] Early in my research into the construction of the "field" concept in physics, I argued that a "family resemblance" view of concept representation affords not only a means of making sense of continuity across major changes in the conceptual structures of scientific theories (Nersessian 1984b; Nersessian 1984a) – Kuhn's "revolutions" – but also provides better interpretations of the historical records of concept formation in the work of an individual scientist (Nersessian 1985). Michael Faraday made the first major contribution to the formation of the concept of field, loosely construed as

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[1] The most prominent among these are by me, Peter Barker, Hanne Andersen, and Xiang Chen.

[2] Hesse also conducted historical research on "forces and fields" which predated her interest in, and cognitive research on, family resemblance accounts (Hesse 1970, *Forces and Fields*, Connecticut, Greenwood Press.).

the idea that processes are taking place in the space surrounding bodies and charges and these processes are necessary to the description and explanation of physical phenomena, initially, electricity and magnetism. Faraday did not use the term “field” until late in his research[3] and so at the time of my analysis it was a matter of considerable debate among Faraday experts as to when he could be interpreted as “having a field concept”. In “Faraday’s Field Concept”, (Nersessian 1985) I argued that the major historical – and conflicting – analyses of Faraday’s contributions to its formation all suffered from not asking the prior meta-question of “what is a concept”, (i.e., the nature of its representation) and that each was accepting, implicitly, the definition (“necessary and sufficient conditions”) account of concept representation I argued, instead, that a family resemblance account (at that time, the “prototype” account) enabled making sense of Faraday’s research as contributing to the construction of the electromagnetic field concept from at least 1832 (with the introduction of magnetic “lines of force”[4]) onwards without having to attribute to him at the outset his mature account or the so-called “essential” features of the modern concept. A family resemblance account, then, is not only fruitful for philosophical analysis, but an important tool for historiographical analysis (see, e.g., Cohen 2010). Although not discussing metaphor per se, family resemblance representations display metaphoric relations, as depicted in Figure 1, an imaginative illustration by my former student of both the broader metaphoric dimension of “field” and also Maxwell’s starting point for the construction of a different, though family-related, field concept.

Finally, as I argued in 1984b, accounting for the continuity between different field concepts from Faraday to Einstein and thus their *commensurability* requires more than just a representation of their family resemblances. Reasoning relations among the features of the instances also needs to be represented. I proposed developing a schema representation of family resemblances along

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[3] Faraday’s first use of the term “field” was in his diary (Faraday 1932; November 1845, 7979) in reference to non-magnetic objects (“if the Sealing Wax, or Asbestos or paper was in the magnetic field”) where the magnetic field is understood as the expanse between two magnetic bodies. Later he elaborates with an intriguing analogy (*Ibid*. 8014) “If a man could be in the Magnetic field, like Mahomet’s coffin, he would turn across the Magnetic line, provided he was not magnetic” (legend had it that Mahomet’s coffin in Medina was suspended in the air). The first published usage is in Faraday 1831-1855 (Vol. 3, 1851: 2086) where he defined “field” in terms of lines of force.

[4] In Faraday 1831-1855: 217-ff., he speculated that electromagnetic induction might take place through the “cutting” of the lines of force surrounding a magnetic source. At the same time he placed a sealed note with the Royal Society to establish his priority with respect to the position that “when a magnetic acts upon a distant magnetic or piece of iron, the influencing cause… proceeds gradually from magnetic bodies and requires time for its transmission which will probably be found to be very sensible. I think also, that I see reason for supposing that electric induction (of tension) is also performed in a similar progressive way” (Williams 1965: 81).

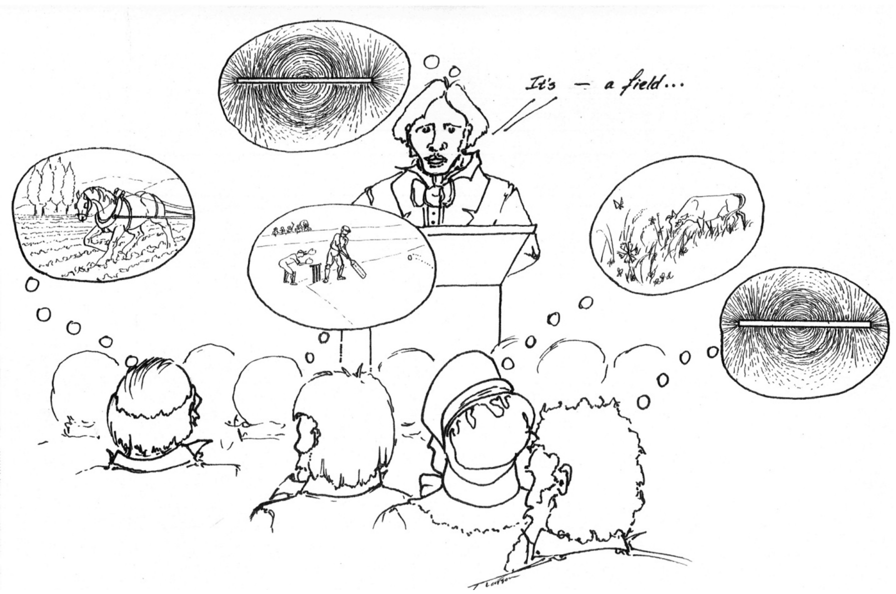

Fig. 1 – A rendition of an imaginary lecture by Faraday with Maxwell in the audience by Anne Larsen.

various dimensions pertinent to scientific concepts and further connected through "chains of reasoning" – a notion borrowed from Dudley Shapere (Shapere 1980; 1982). Much of that reasoning takes the form of analogical inference, which, coupled with imagistic and simulative ("thought experiment") reasoning, is what I would later call model-based reasoning.

As with the science case, a pure "feature-based" notion of family resemblance was found to not fully capture mundane practices which seemed to be employing rudimentary reasoning with intuitive "theories" about relations among features in categorization (see Smith and Medin 1981 for various arguments and proposals). To take a simple example, relations between beak shape (round or pointed) and foot type (webbed or clawed) are important to categorizing something as an instance of "water bird" (round and webbed) or of "land bird" (pointed and clawed). One major proposal by the cognitive psychologist Lawrence Barsalou, "dynamic frames" (Barsalou 1987; 1992), has been profitably exploited in case histories of conceptual change in science, most notably by the "ABC" (Andersen *et al.* 2006) research group. With a dynamic frame representation, various attributes are mutually constraining (e.g., beak and foot), so at any slice in time, a concept is represented by a set of interconnected constraints. These constraint relations can change over time as new attributes are added (feathered or non-feathered) and new information is accommodated. The discovery of screamers (birds that have pointed beaks and webbed feet) led to new features being added to the frame for "bird" and the classification "water bird" or "land bird" being changed to finer distinctions (see Andersen *et al.* 2006). As I will discuss in the next section, dynamic frame representations of concept relations are also quite useful from the perspective of model-based reasoning.

3. *The analogical nature of inference*

There is widespread agreement in cognitive science on the importance of analogy in creative thinking and that analogy is a "mechanism" of conceptual change in cognitive development and in science. This agreement has come about through the interaction of research in cognitive science and in the history and philosophy of science, although in general scant attention in philosophy of science has been directed towards analogical reasoning. As I noted at the outset there is a significant literature on models, and given Hesse's connection of models with analogies, one would expect literature on the former to address the latter. Instead the philosophical models literature has tended to emphasize the "realism" issue with the question of how "false models" can support predictions or provide explanations. But this becomes a less interesting problem if one understands models as analogue representations and reasoning by means of models as form of analogical reasoning, because the source model is always a "false" representation in that it does not accurately represent all the characteristics of the target phenomena, and, as Hesse pointed out, there are different and neutral features as well. The cognitive science literature on analogical reasoning, on the other hand, pays scant attention to the representational considerations in analogical reasoning beyond discussing the need for adaptation (usually via abstraction) in mapping and transfer processes. Here I will briefly discuss the current state of the cognitive literature and then turn to an important facet of analogical reasoning in creative problem solving in science not addressed by that literature, including Hesse, and argue that attending to this facet makes clear there is a significant linkage between models and analogies in science.

3.1. Cognitive science research on analogy

The main foci of the analogy literature in cognitive science have been the processes of retrieval, mapping, and transfer. It is not possible to go into the details of the numerous cognitive accounts of analogy here. Instead, I will outline the most relevant findings and interpretations for thinking about analogy in science, mainly drawing from cognitive psychology (although many theories have also been instantiated in AI programs). All the psychological research on analogy assumes that in problem solving source analogies are ready-to-hand – they are prior problem solutions the reasoner either has encountered or, in experimental situations, been given. The experimental research on analogy is vast, but the main finding, starting from the earliest research (Gick and Holyoak 1980) about retrieval, is that it is very difficult to achieve in experimental situations, but appears relatively easy "in the wild" (e.g. Dunbar and Blanchette 2001). In a typical analogy experiment (e.g., the Dunker "radiation problem" and its analogues), subjects (usually undergraduates) are given a story to read (such as the capture of a fortress), some distracting stories, and then asked to solve a problem (in this case how to kill a tumor without destroying neighboring tissue). An important difference between the experimental and real-world outcomes lies in the fact that when people make spontaneous analogies in meaningful problem-solving contexts, they draw on sources with which they are familiar, whereas the psychological experiments require them to recall and use what they have just learned to solve problems that are not their own. Retrieval improves when subjects are given a hint or, even better, the opportunity to solve several problems using the source and analogues of it (Faries 1988; Gick and Holyoak 1980; 1983; Schumacher 1988). One highly significant difference between the cognitive research and the cases of analogy I have studied is that unlike the experimental studies on which the cognitive theories of analogy are based, there are no ready-to-hand analogical problem solutions to transfer directly from source to the target problem. Rather the source analogy itself needs to be constructed. I will discuss this analogy-building process after addressing the cognitive research on mapping and transfer.

Hesse (1963: 65-66) noted that in all analogies there are "two sorts of dyadic relation", among the properties of the source and target, viz., "horizontal" (similarity) and "vertical" (usually, causal). Analogical reasoning then consists of determining and exploiting the identities and differences among these relations. Cognitive research, generally, has established that productive analogies largely rely on relational structures among the properties (vertical) rather than among the properties (horizontal). The "structure mapping" criteria proposed by psychologist Dedre Gentner (1983) (which are widely agreed on in cognitive science) are: (1) structural focus (preserving relational structures); (2) structural consistency (making isomorphic mappings between systems); and (3) systematicity (mapping systems of higher-order, interconnected relational structures) (Clement and Gentner 1991; Gentner 1983; Gentner *et al.* 1993b).

There are two features of Gentner's criteria that make novel and significant contributions to understanding analogical reasoning. First, the focus she places on mapping relational structures (causal and other), which leverages off of Hesse's 1963 account noted above, is especially important for understanding the productivity of these practices in science. Analogical reasoning cannot be evaluated as "sound" in the logical sense, where true premises and good reasoning lead to true conclusions. But there are ways of differentiating instances of good analogical reasoning from less useful or bad. Gentner's criteria provide a means for evaluating the "goodness" of an analogy: that is, for determining what makes a particular analogy productive when it has proven fruitful and for thinking about how to make productive analogies (Gentner *et al.* 1993a). Second, Gentner's systematicity criterion is a novel and valuable insight. It is not mapping of relations alone, but mapping of interconnected structures of relations – i.e., maintaining higher-order relations among relations – that tend to make analogies most productive. Accessing a systematic representation of knowledge in the source domain provides a series of *interconnected inferences* to apply to the target. In the fortress – tumor problem, for example, mapping of the interconnected relational structure "dividing the army avoids the mines and causes the capture of the fortress" leads to the inference that distributing the rays will avoid tissue damage and cause the death of the tumor.

However, analogy use in science and elsewhere diverges from Gentner's theory of structural alignment and projection. Her account does not consider the goals of the problem solver in mapping and transfer. The structures of relational matches are transferred as identities (even if some re-representation is required to achieve this) and candidate inferences are made on the basis of systematicity in the source domain. Gentner and colleagues argue that a general theory of analogy as a cognitive capacity needs to capture all forms, including literary comparisons, proportional analogies, problem solving, and reasoning. They argue, for instance, that people can process analogies without any goals, such as when a person understands an analogy they simply hear or read (Forbus *et al.* 1998). The core of an analogy does lie in a relational comparison, but what relations are to be compared and how are they selected? These questions are particularly salient in problem solving by means of analogy. Keith Holyoak and Paul Thagard (1996) argue, that at the very least, transfer requires evaluating the plausibility of an inference in the context, and thus pragmatic information, such as the problem-solving goals, helps to determine the candidate mappings and what to transfer, and, they argue, are operative in all of the processes of analogy. They base their claim on extensive psychological studies by Holyoak and studies of scientific analogies by Thagard. For the analogies I have studied in the history of science and in contemporary practices in the bioengineering sciences problem-solving goals direct retrieval, mapping, and transfer processes. The general pattern of these and other exemplars is that the target constraints and the goals of the problem guide the selection of the salient relations and, thus, the candidates for mapping and transfer within the source domains. These, in turn, provide additional constraints on constructing models through which the problem solver reasons about the phenomena in question. What mapping is made between the model and the target and what inferences transfer is guided by the interpretation and goal in play at the stage of the problem solving.

However, as I have argued (Nersessian 2008), there is a significant *representation-building* aspect of analogy that is evidenced in several data sources – historical, think-aloud protocols, ethnographic studies. This aspect points to significant processes that are neglected in both the philosophical and cognitive science literatures: often in cutting-edge research, there is no ready-to-hand problem solution that can be retrieved and adapted analogically from a source domain. Rather, what are customarily thought of as analogical source domains only provide some constraints that interact with target constraints and are incorporated into intermediary models, which are constructed to serve as analogical sources for the target domain. That is, the constructed model is built explicitly to provide a comparison to the target phenomena based on analogy. As will be discussed in the next section, the core of the problem-solving process consists in building models that embody constraints from the target phenomena and possible analogical source domain(s), solving problems in the constructed models, and then transferring the solution as a hypothesis to the target phenomena.

3.2. Model-based reasoning

Approaching analogy from the problem of how novel concepts are constructed in science (as candidate representations for conceptual change), provides an account of how reasoning and representation interact in the course of problem solving: through iterative model construction, evaluation, and adaptation processes directed toward creating a representation adequate for solving the target problem. Such "model-based" reasoning can employ mental, physical, or computational representations that are structural, functional, or behavioral analogues of target systems. Further, models can be represented visually and have simulative capabilities. For example, Maxwell (1861-2) represented his "physical analogy", i.e. the idle wheel – vortex model of the electromagnetic aether, as a diagram accompanied by text for animating it (simulating in imagination).

So-called "revolutionary" conceptual change raises a significant problem: given that we must start from existing representations, how is it that we can create something genuinely novel? This problem lies at the heart of the post-

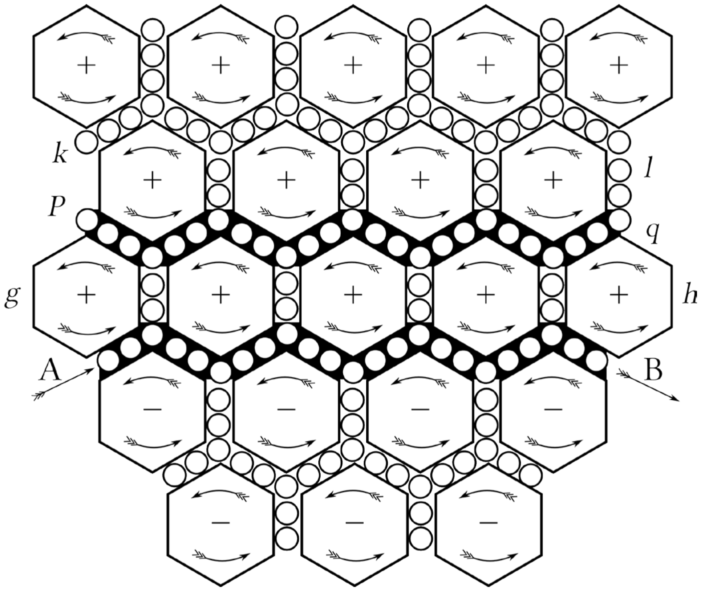

Fig. 2 – Maxwell's diagram of the vortex-idle wheel model
(Maxwell 1890, Vol. I, Plate VIII)

positivist problems of "meaning change" and "incommensurability". The electromagnetic field representation in physics is one such exemplar: using the representations resources of continuum mechanics (Newtonian source domain), Maxwell constructed a mathematical representation of a non-Newtonian dynamical system. I have argued that the reasoning Maxwell used, which he called "the method of physical analogy", is representative of a form of problem solving overlooked in cognitive and philosophical literatures. In this form of problem solving by analogy, there is no ready-to-hand analogue problem solution in a source domain – the source itself needs to be constructed. I have argued that this form of problem solving requires an *interactive* account of analogy where target and source constraints interact in the process of building intermediary models.

Instead of mapping and transferring features directly to the target, specific constraints of a source domain are abstracted on the basis of, and combined with, constraints stemming from the target to create intermediary, i.e., hybrid models, which in turn possess their own constraints. The intermediary models are constructed to serve as analogical sources for the target problem. Thus target and source domains interact through the construction of intermediary models and inferences about the target domain are mapped and transferred from the intermediary models. Problem solutions derived in the model provide candidate solutions for the target. The hybrid models afford exploring novel *combinations of constraints* not represented in either target or source domain, and thus genuinely novel representations, including novel concepts, can emerge. It is conceivable that a single constructed model could suffice to provide a problem solution, but in the cases I have examined from different domains (electromagnetism, mechanics, and various bioengineering sciences), the process involves incremental bootstrapping with cycles of abstraction, construction, evaluation, and adaptation and with each constructed model building upon the previous to some extent while moving farther from the starting point (see Figure 3). The final outcome of this process, for instance in the Maxwell case, was that he was able to abstract a generic, general dynamical representation for potential energy and kinetic energy that could be used to

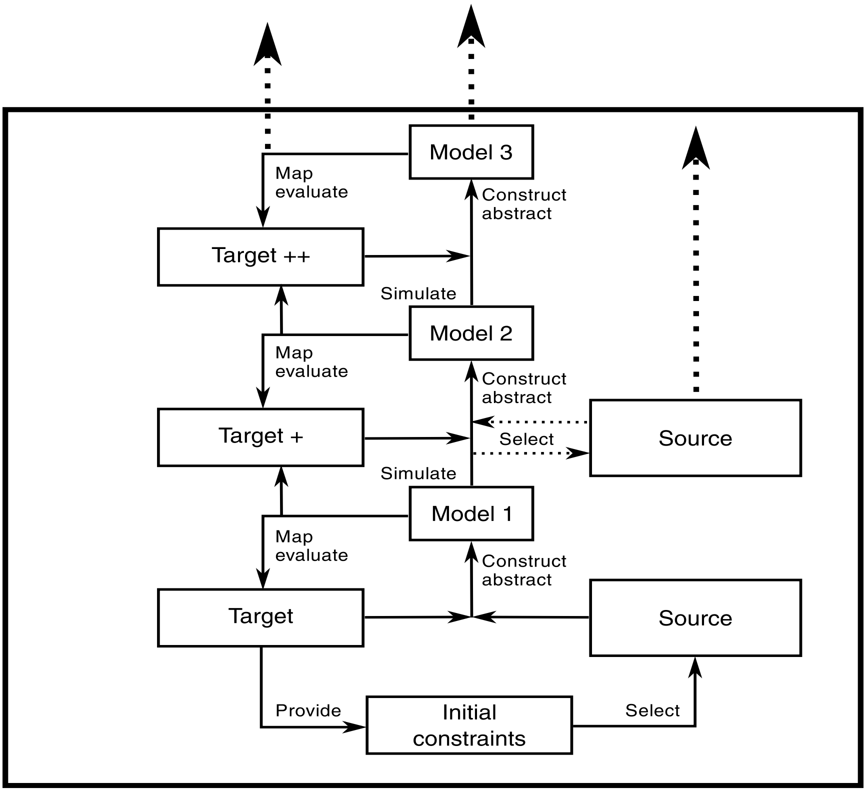

Fig. 3 – Bootstrapping to a problem solution via the construction of intermediary models (Maxwell 1890, Vol. I, Plate VIII)

re-derive the equations without the model – but he only arrived at that representation through the prior analogical modeling process.

This constraint-based account of constructing analogue models fits well with the dynamic frames account of concept representation, especially as it pertains to scientific concept formation and change. If a concept is represented by an interconnected set of constraints, then concept formation and change are processes ranging from modifying constraints in existing representations to creating sets of genuinely novel constraints. The two accounts together link the family resemblance nature of concepts with the analogical nature of inference.

The initial account of model-based reasoning and interactive analogy has drawn from historical and experimental research. Since then it has been extended to cognitive practices in cutting-edge research in the bioengineering sciences in which physical (*in vitro*) and computational models are designed and built to serve as sources for investigating real-world (*in vivo*) phenomena that integrate selected constraints from biology, engineering, and modeling platforms (in the case of computational models). These practices put analogical inference at the center of problem solving where little is known about the target phenomena and conceptual innovation and change are on-going processes. In the next section I discuss these practices to illustrate the account I have presented in this section and show its wider applicability.

3.3. Constructing analogue models for investigation in bioengineering sciences

Recent investigations into the problem solving practices of pioneering laboratories in the bioengineering sciences conducted by my research group have uncovered entire fields that conduct research by designing and building analogue models. Bioengineering sciences conduct basic biological research in the context of application problems. For instance, one laboratory conducts research into the effects of fluid flow through blood vessels that has been contributing novel findings to endothelial cell biology in the process of attempting to develop an artificial artery for implantation. Issues of control and, often, ethics, make it not possible to experiment on target in vivo phenomena. Instead research in these laboratories is conducted by means of what they call simulation "devices" – in vitro bio-engineered physical simulation models that are designed and built to serve as structural, behavioral, or functional analogs to selected aspects of in vivo phenomena. These models provide a means of investigating selected aspects of "normal" in vivo behavior in vitro as well as of counterfactual situations ("If we were able to do X, Y, Z to the in vivo phenomena, what would the outcome be?"). The devices participate in experimental research in various configurations of hybrid "*model-systems*".[5] As one researcher put it: "*I think you would be safe to use that [notion] as the integrated nature, the biological aspect coming together with the engineering aspect, so it's a multifaceted model-system*". Simulation models are designed to function as analogical sources for inference and prediction about target in vivo systems. They are constructed so as to enable the researcher "*to predict what is going to happen in a system [in vivo]. Like people use mathematical models... to predict what is going to happen in a mechanical system? Well, this [in vitro model-system she was designing] is an experimental model that predicts – or at least you hope it predicts – what will happen in real life*". That is, research is conducted with these in vitro devices and outcomes are transferred as candidate understandings and hypotheses to the in vivo phenomena. Our research has also established the role played by these simulation models in concept formation, such as "arterial shear" in the endothelial cell case.

For this research we investigated the cognitive practices of two laboratories, "Laboratory A", conducting tissue engineering research and "Laboratory D", conducting neural engineering research. Our research group conducted an ethnographic study (field observations and largely unguided interviews) that sought to uncover the activities, tools, and meaning-making that support research as these are situated in the ongoing practices of each community. For each laboratory we conducted 2 years of intensive data collection, followed by 2 years of targeted follow-up and, thereafter, limited tracking of students through to their graduation. We took field notes on our observations, audio taped interviews, and video and audio taped research meetings (full transcriptions are completed for 148 interviews and 40 research meetings), and collected a range of historical data pertaining to each laboratory (including. notebooks, paper drafts, email, grant proposals, powerpoint presentations). The next sections provide synopses of two exemplars of investigation through iterations of designing and constructing analogue physical and computational simulation models we have examined in detail elsewhere.

3.3.1 Articulating "arterial shear"

The first exemplar demonstrates how the problem of articulating a multidimensional concept gave rise to building a range of physical simulation models to serve as analogical sources for investigating the phenomena that would become features of "arterial shear".[6] Laboratory A is a tissue engineering laboratory that dates to 1987, when the director decided to "*take the research in vitro*",

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[5] Italicized quotes are statements of laboratory researchers drawn from our interviews.

[6] For an extended discussion of this case see Nersessian 2012; Nersessian and Patton 2009.

mainly because problems of control with animal studies were limiting research possibilities. Along with a handful of other researchers, he started to develop a hybrid concept, "arterial shear": the frictional force of blood flow parallel to the plane through the lumen of an artery.[7] The concept is hybrid in that features of it are drawn from biology and from engineering. What the research community now understands to be among the interrelated features of arterial shear are: it regulates endothelial cell migration, morphology, and proliferation; laminar flow is needed for these functions; and turbulent flow creates changes that promote vascular constriction and platelet aggregation. During the time Laboratory A has been in existence, its research has expanded from investigating macroscopic features to the functioning of the cells themselves, and, most recently, the processes of stem cell differentiation into endothelial cells.

The two main physical models that were iteratively designed and built by the laboratory are the "flow loop" and the "construct". Together they comprise a model-system that simulates to various approximations the flow of blood through the lumen in an artery. The initial model-system of Laboratory A was the flow channel device (referred to as the "flow loop" within the laboratory), which is designed to parallel selected in vitro blood flow conditions, normal and pathological. It consists of a flow channel (designed in a physiologically meaningful range) with accompanying flow inducing components (pump, pulse dampener, and a liquid that has the viscosity of blood). During operation the flow loop provides a 1st order approximation of the shear stresses during blood flow in an artery. When cells mounted on slides are "*flowed*" under different conditions, changes in cell morphology can be related directly to the controlled wall shear stresses. Even though the flow loop is a concrete physical model, the researchers think of simulations with it as "*something very abstract because there are many in vivo environments and many in vivo conditions within that environment, Things change constantly in our bodies over our lifetimes, including the physiological flow rates*". Thus they recognize the limitations of their model as an analogical source from the outset.

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[7] I have not been able to track down precisely when and where this term came into use, but given that the Laboratory A director collaborated with some other researchers at that time, it could have had multiple "baptisms". For our purposes what is most important is how it drove the setup of Laboratory A and the line of in vitro research we witnessed during our investigation. In the cases discussed in this paper, a close connection will be evident between concepts and what might be considered the developing theories of the phenomena. This is in line with philosophical accounts that advocate understanding a concept to be represented by the set of interrelated features or characteristics ascribed to it by a theory, or by the scientists who are using it when no developed theory exists (see, e.g., Arabatzis 2006; Nersessian 1984b). It is also in line with cognitive science accounts discussed earlier, most notably the "dynamic frames" analysis of Barsalou 1992 which has been applied to scientific concepts by Andersen *et a*l. 2006.

Another limitation is that using cell cultures on slides can provide only limited understanding of arterial shear stress in the vessel. As the director noted, "*putting cells in plastic and exposing them to flow is not a very good simulation of what is actually happening in the body [...] If you look within the vessel wall you have smooth muscle cells and then inside the lining are the endothelial cells, but these cell types communicate with one another. So we had an idea: let's try to tissue engineer a better model-system for using cell cultures*". So, to develop an understanding of the functional properties related to shear, the laboratory spent considerable effort to create "*a more physiological model*" where the effects of shear could be studied on more components of the blood vessel wall than the endothelial cells in isolation. To expand the possibilities for studying biological responses they undertook to "*tissue engineer*" a better analogue: a living model of the blood vessel wall, now called "*the construct*" or "*tissue engineered vascular graft*" (denoting its application potential).

The in vivo blood vessel comprises several layers: the lumen where the blood flows, a first monolayer of endothelial cells that sit on collagen, an internal elastic lamina; a second layer of smooth muscle cells, collagen and elastin, an external elastic lamina; a third layer of loosely connected fibroblasts, which are cells that secrete collagen and an extracellular matrix of proteins and other molecules. The in vitro construct comprises a family of analogue models since it can be created with different levels of approximation for simulating in vivo processes; for instance, it can be seeded with both cells types or only one and can comprise all or only one layer. The construct model, in turn, has given rise to several other physical models through which to investigate construct properties under various conditions and also to a novel applied goal: to tissue engineer a viable replacement blood vessel for human implantation. For use in conjunction with the flow loop, constructs are cut open and placed flat in the chamber. Researchers contend that nothing significant is different in the flow the cells experience in the flat construct as compared with the tubular blood vessel because "*from the cell's perspective*", given its size relative to the blood vessel diameter, "*the cell sees basically a flat surface... the cell has no idea that there's actually a curve to it* [vessel]". So they infer that the forces that the cells experience on the flat construct will not differ significantly for their purposes.

When we entered the laboratory, the construct model, was the focal point of the interconnected research problems directed towards both what the director called the laboratory's "*basic biology*" research aimed at continuing to articulate "arterial shear" and the new application goal of creating a viable vascular implant. Although it is not possible to go into the details of the groundbreaking research conducted with various iterations of these analogue models, inferences drawn from these simulations have been contributing to the field's understanding of arterial shear and of basic endothelial cell biology. The building of the flow loop model enabled the researchers to focus largely on structural properties of cells under shear and proliferation behavior. Devising the construct family of models provided not only a range of analogue models, but also the possibility of investigating blood vessel wall's functional properties in relation to shear.

3.3.2 "Learning" in neural networks and the concept of "CAT"

During our investigation, Laboratory D's overarching research problems were to understand the mechanisms through which networks of neurons learn and, potentially, to use this knowledge to develop aids for neurological deficits and diseases. At the time the Laboratory D director began research, the major approach to neuron learning was through single neuron studies on living animals, where one might gauge responses to stimuli, but not control supervised learning. Parallel to the Laboratory A case, a novel problem of conceptual articulation was at the forefront of this research. In this case, the problem was how to conceptualize "learning at the neural level" as a network phenomenon.[8] The laboratory director believed that to study learning there needed to be a way to investigate the network properties of neurons and he had the idea that "*perhaps you can make cell culture systems that learn*". Such a culture would more closely model learning in the brain and also enable emergent properties to arise and be studied. The primary model-system of the laboratory is an in vitro physical model, *the dish*, and associated technologies for stimulating, recording, and optically imaging activity of the cultured neuron network. This model-system was and has continued to be designed and constructed over years of iteration. Building the iteration of the in vitro dish model-system used by Laboratory D during our investigation requires extracting cortical neurons from embryonic rats, dissociating their connections, and plating them (15-60K, depending on the desired network) on a specially designed set of 64 electrodes called a "*multi-electrode array*" (MEA) where the neurons regenerate connections to become a network. The dish model-system is a hybrid entity whose design incorporates constraints, methods, and materials from neurobiology, chemistry, and engineering. It provides a generic model of network processing of cortical neurons. Although a greatly simplified model, the research group (and the field) takes it to provide an analogue source for making hypotheses for how cortical neurons learn in vivo

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[8] For an extended discussion of this case see Nersessian 2012b and Nersessian & Chardrasekharan 2009.

The group's initial understanding of phenomena exhibited by the in vitro model was in terms of concepts borrowed from single neuron studies (spike, burst) and engineering (noise). They understood that the emergent properties of the network might require extension or modification of these concepts. In practice, these transferred concepts both facilitated and impeded the research. The concept of spike (action potentials or nerve impulses) facilitated developing stimulation and recording methods and interpretations of the output of clusters of neurons surrounding an electrode. The concept of burst, when extended to spontaneous dish-wide electrical activity, and categorized as noise in the engineering sense of interference (in this case with learning), and thus something to be "quieted", impeded the research for an extended period. The dish of neurons continually exhibited bursting and it took over a year to figure out how to quiet it with electrical stimulation. However, once quieted, the research reached an impasse in that attempts to induce learning (constant response to a stimulus) failed.

To deal with the impasse, one researcher introduced a new modeling method into the laboratory research, computational simulation of a physical model. This led to the formation of a cluster of novel concepts, which together enabled them to understand that bursts could be signals (as well as noise). If bursts were signals, then they could be exploited to create supervised learning in the dish. This computational model was constructed to eventually provide an analogy to the physical model; that is, once the computational model had sufficiently replicated in vitro dish behavior, inferences made about the phenomena taking place in it were to be transferred to the in vitro model, and potentially from there to the in vivo phenomena. The computational model is also hybrid in that it merges modeling constraints, intra-domain constraints from other areas of neuroscience (brain slices, single neuron studies), and dish constraints.

It is not possible to go into the details of building the computational model here, however it is important to understand that the initial computational 'dish' was built not on the experimental data from their in vitro dish, but by drawing from intra-domain sources in neuroscience; in particular, from studies involving single neurons, brain slices, and other computationally simulated networks. The initial constraints the computational model adapted from their in vitro dish were not based on their experimental outcomes (i.e., the behavior of their dish), but had to do with the construction of the dish. These included the area of the neurons, the placement grid of electrodes, the number of electrodes used for recording and stimulation, and the random location of the neurons. His model was tested and optimized with data from other MEA dishes first, and then their own. The model, as developed, provides a computational simulation of the activity of a *generic* in vitro dish. As with the conceptual and physical models, the computational simulation of a physical dish model was developed and optimized through a bootstrapping process comprising many cycles of abstraction, construction, evaluation, and adaptation that included integrating constraints from the target (their dish model) and analogical sources domains (a wide range of neuroscience literature), as well as constraints of the computational model itself (the modeling platform and those that arose as the model gained in complexity).

Developing the computational model involved creating a novel visualization of the dish activity that proved to be highly significant in solving the supervised learning problem by means of articulating a cluster of conceptual innovations. By means of the dynamic visualization, the group began to notice something interesting: there were structurally similar looking bursts and there seemed to be only a small number of "patterns of propagation" of these. These patterns were novel and distinct from what they had been able to observe in vitro and, potentially, could provide new insight into its behavior. The visualization of the network's activity shows the movement of an activity pattern across the entire network, in real time. In the *in vitro* model-system the system activity is hidden among recordings of the spiking of clusters of neurons around individual electrodes. The computational visual representation of activity at the individual neuron level led to the conclusion that: "*… the spontaneous activity or spontaneous bursts are very stable*". The next step was to attempt to develop a means of tracking the activity of the possibly "stable" bursts across the network.

From this point, things developed rapidly as the group worked together on statistical analyses and on experimentation to see whether measures developed for the computational network could be transferred to the in vitro dish, and whether the "burst feedback" in the in vitro dish could be used for supervised learning in robotic embodiments of the in vitro dish. They began to develop the concept of bursts as signals (rather than only noise) that might be used to control learning. Articulating the notion that bursts can be signals took the form of several interconnected novel concepts: "burst type": one of a limited number of burst patterns (10); "burst occurrence": when a type appears; "spatial extent": an estimation of burst size and specific channel location; and "CAT" ('center of activity trajectory'): a vector capturing the flow of activity at the population scale. With the exception of 'spatial extent' all of these concepts were developed for the computationally simulated network first and then mapped to the in vitro dish and modified as required. Although each of these concepts is important, they are quite complex conceptually and mathematically, "CAT" is an entirely novel concept for understanding neural activity and could prove to be of major importance to neuroscience. CAT tracks the spatial properties of activity as it moves through the network; that is, *the flow of activ-*

ity at the population scale. It is an averaging notion similar to the notion of a population vector, which captures how the firing rates of a group of neurons that are only broadly tuned to a stimulus, when taken together, provide an accurate representation of the action/stimulus. CAT differs from a population vector and is more complex because it tracks the spatial properties of activity as it moves through the network. What the CAT analysis showed is that in letting the simulation run for a long time, only a limited number of burst types (classified by shape, size, and propagation pattern) occur – approximately 10.

3.3.3 Summary

The primary investigative practice in many areas of biomedical engineering science is constructing in vitro and computational models through which to gain understanding and control of in vivo phenomena. Thus, models are built towards becoming analogical sources. From the outset, the intention is to build an analogy but the nature of that analogy is determined incrementally, over time, with only certain features of it selected at the time of building. Often, to build an analogy requires configurations of more than one model, comprising both engineered artifacts and living matter. These "model-systems" are dynamical entities that perform as structural, functional, or behavioral analogs of the in vivo systems. Through experimenting with them, researchers develop hypotheses that they "hope [will] predict…. what will happen in real life". Our investigations of ongoing problem-solving practices establish that model-based reasoning has been contributing to conceptual innovation and change across a wide range of sciences and historical periods and on into present-day science. Of course, the specific kinds of modeling possibilities have enlarged over the history of science bringing with them new affordances, for instance, those of dynamical simulation and visualization of the sort afforded by computational modeling. Still, the model-building processes in these and other cases from our ethnographic studies exhibit the same kind of process in the abstract as represented in Figure 2 which was derived from historical cases and problem-solving protocol studies:

- analogical domains: sources of constraints for building models
- imagistic representation: facilitate perceptual inference and simulation
- simulation: inferences to new states via model manipulation
- cycles of construction simulation/manipulation, evaluation, adaptation
- emergent analogical relation between the model and the target

To use a notion drawn from ethnographic analysis, this kind of conceptual innovation process *transfers* robustly across different time periods and also across several sources of data and methods of analysis.

4. *Conclusions*

Hesse argued that the metaphorical nature of scientific language is best realized as a "family resemblance" account of concepts from which it follows that scientific reasoning is fundamentally analogical. The turn of contemporary philosophy of science to practices has moved away from analysis of the language of theories to the roles of models in the application of theories to the world. I have argued that examining the practices of how models are created in discovery reinforces her notion that models are closely bound with analogies – indeed, in scientific practice, models frequently are built explicitly to serve as analogical sources. Thus a richer understanding of the nature of the intellectual work done with models requires an account of analogical reasoning. Progress is made by combining insights from cognitive-historical and ethnographic studies of scientific practices and research on mundane cognitive practices. Much cognitive science research has been directed towards explicating retrieval, mapping, and transfer processes of analogy. Scientists often make use of retrieved analogies, but in cutting-edge scientific research there is likely to be no ready-to-hand analogical source and here the significance of the representation-building dimension of analogy comes to the fore. Representation building involves interaction of target and source constraints, towards building intermediary models that embody features and constraints of both. The process iterates until a problem solution is found in a model that can successfully be mapped and transferred to provide a tentative solution to the target problem. These processes often promote concept formation and change since in the process of generating and altering constraints among features represented in the models, novel features and constraints can emerge in problem solutions. The representation of these constraint-based scientific concepts aligns with the cognitive science notion of concept representation in terms of dynamic frames (an account developed from the family resemblance character of concepts).

Acknowledgements

I appreciate the support of US National Science Foundation grants REC0106733, DRL0411825, and DRL097394084 in conducting the laboratory studies. These investigations were carried out over a period of twelve years with the numerous members of my Cognition and Learning in Interdisciplinary Cultures research group at the College of Computing, Georgia Institute of Technology to whom I am grateful, especially to my co-PI, Wendy Newstetter. I appreciate the comments of two reviewers of this journal and the editor of this issue.

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