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Symbol Systems as Cognitive and Performative Hybrids: A Reply to Axel Gelfert
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Symbol systems such as mathematical formalisms, diagrammatic methods, and visual symbol systems are used widely in science as representational resources and often give rise to what are generally referred to as 'scientific models'. This has led to an extensive philosophical debate on the nature of such models (for an overview see Frigg and Hartmann 2012). While many philosophers have discussed models in terms of realisms and truth, pragmatic viewpoints are often underrated, in particular when it comes to the individual researchers' ability to apply and advance such symbol systems. Axel Gelfert's paper argues for a pragmatic perspective and recognizes the work of Mary Hesse and Nelson Goodman as advancing interesting theories concerning the individual and collaborative use of models (Hesse 1963; Goodman 1976).

Hesse's concept of models as 'pointers towards further progress' with their 'own *ways* of suggesting and generalisation' as well as Goodman's concept of 'denotation' based on individual decisions guided by prior collective usage ascribe a pivotal role to the scientific community in applying and advancing symbol systems (Gelfert 2015, 54-56). Regarding mathematical formalisms as 'pointers towards further progress', Gelfert states that they require 'the backdrop of a scientific community whose members are skilled in applying and modifying models and theories, and which, collectively, is able to arrive at determinations regarding the fruitfulness (or 'progress') of new theoretical proposals' (Gelfert 2015, 57).

In support of his arguments Gelfert provides the example of Feynman diagrams, developed by Richard Feynman in the 1940s as individual tools in order to master complex computations in quantum electrodynamics (QED) (Feynman 1949). During the 1950s his graphical method increasingly shifted from a 'bookkeeping device for simplifying lengthy calculations' into a tool that changed 'the way physicists saw the world' (Kaiser 2005, 156). Feynman diagrams turned from individual tools into a communally adopted and 're-tooled' notational *lingua franca* of high-energy physics (Gelfert 2015, 58). In other words: 'What has started off as an initially arbitrary notational system, [...] quickly acquired a degree of social and institutional reality that would shape the behaviour and cognitive processes of theoretical physicists' (Gelfert 2015, 59). The question of why these diagrams have become so successful, however, is only partly answered by Gelfert. He advocates the 'external mind view' as for him diagrams and other symbol systems are fruitful because they externalize scientists' cognitive load by outsourcing inferential work (Gelfert 2015, 59 et seq.). However, this does not fully explain why this method, and not others, has become the notational *lingua franca*.

Symbol Systems as Cognitive Hybrids

The kinds of symbol systems referred to here are direct or indirect mathematical formalisms. While direct mathematical formalisms operate on equations and other mathematical notations, indirect ones translate diagrammatic and visual notations into mathematical ones. Feynman diagrams, as well as the structural formulas of chemistry, are good examples of the latter. What is so astounding for philosophers is that although these symbol systems are produced by individuals, they can successfully meet an objective and collective need. In this sense, symbol systems are cognitive hybrids of individual and social, subjective and objective knowledge. In order to explain both the cognitive hybridity and the success of a specific symbol system, educational training is usually mentioned, but perhaps there is another explanation as education does not completely explain the creative achievements of individuals and their fruitful socialization and standardisation.

While the 'miracle' of math's objectivity and applicability has occupied the philosophical debate for decades (Wigner 1960; Popper 1972; Steiner 1998; Gelfert 2014), only recently has the 'philosophy of mathematical practice' begun to pay attention to the social circumstances of mathematics and the various mathematical practices beyond logical reasoning: e.g., practices such as visualisation, simulation, and diagram-based reasoning (Ernest 1998; Heintz 2000; Humphreys 2004; van Kerkhove and van Bendegem 2007; Mancosu 2012). However, except for the work of the sociologists Paul Ernest (1998) and Bettina Heintz (2000), neither has the philosophy of mathematical practice shown much interest in studying the individual/collective transition points beyond merely educational arguments. Therefore an applied philosophical and case based approach to mathematics may be helpful to understand the above mentioned astonishment better beyond social analysis.

By analyzing David Kaiser's (2005) historical study and Axel Gelfert's (2015) philosophical interpretation in more detail, three interesting aspects can be identified:

1) Higher-Order Analogies

In contrast to Hesse's definition of models as analogies (Hesse, 1963, 201), an analogy (in a higher-order sense) refers to the representational link not between models and nature, but between models and other models; or, more generally speaking, between distinct forms of representations. As Gelfert points out, Hesse's approach already went beyond the direct representational link of traditional models–concrete and mechanical models–as for her, any system can be a model. Thus, on the one hand, establishing an analogy with nature becomes indirect and labor-intensive; on the other hand, the representational liberation opens up the 'mathematical formalism itself' as 'pointers towards further progress' (Hesse 1963, 200). Mark Steiner, in the context of quantum mechanics, has called this new kind of scientific pointers 'Pythagorean and formalist analogies':

> By a 'Pythagorean' analogy or taxonomy at time t, I mean a mathematical analogy between physical laws (or other descriptions) not paraphrasable at t into nonmathematical language. […] By a 'formalist' analogy or taxonomy, I mean one based on the syntax or even orthography of the language or notion of physical theories, rather than what (if anything) it expresses. Because any notion has, itself, a mathematical structure, formalist analogies are also Pythagorean (Steiner 1998, 54).

The relevance of Pythagorean and formalist analogies is twofold. First, the 'discoveries made this way relied on symbolic manipulations that border on the magical. I say "magical" because the object of study of physics became more and more the formalism of physics itself, as though the symbols were reality' (Steiner 1998, 136). Second, these analogies are second-order, or even higher-order analogies, as they are based on properties of properties of descriptions.

2) Media Transgressions

A closer look at the various levels of analogies unveils that piling up analogies is often accompanied by a shift in media, and that creative achievements of individuals often result from individual (creative or imaginative) faculties in translating or transgressing something into another representational form or medium. Feynman diagrams are graphical analogies of amplitudes of probabilities, which are complex numbers, using 'calculational tricks, some of his [Feynman's] own design and others borrowed' (Kaiser 2005, 160). They improve accessibility not only due to the visual character of the graphical representation, but mainly from its organizational possibilities—which would simply be unmanageable in the form of mathematical equations.

3) Individuality and locality

As Kaiser and others reported (Wüthrich 2010; Gross 2012), Feynman's diagrammatic method was not understood and propagated immediately. In fact, his method met with strong resistance within the particle physics community: 'His version of QED was founded upon non-standard mathematical techniques, contained novel physical reinterpretations of fundamental particles, and involved a strange, new diagrammatic method of computing results' (Gross 2012, 185). Other scientists could not grasp the rules for computating these diagrams. The method was too new, and too idiosyncratic. Although Freeman Dyson gave a rigorous interpretation of Feynman diagrams (Dyson 1949), 'local traditions emerged [during the 1950s]. Young physicists at Cornell, Columbia, Rochester, Berkeley and elsewhere practiced drawing and interpreting the diagrams in distinct ways, toward distinct ends' (Kaiser, 2005, 165). Feynman himself developed a 'morphological diversity' of his diagrams (Gross 2012). Obviously, 'whether a representation is successful then might seem to be largely a matter of the (individual) user's intentions and epistemic interests' (Gelfert 2015, 56). Or as Kaiser pointed it out: 'As with any tool, we can only understand physicists' deployment of Feynman diagrams by considering their local contexts of use' (Kaiser, 2005, 165).

To sum up: High-order analogies involve representational liberation; media transgressions bring with them imaginative and organizational liberation; and individuality and locality are accompanied by adaptational liberation. All these liberations challenge objectivity and its characteristics such as strictness, universality, and repeatability. This is not new for laboratory studies of empirical science practices, but it is certainly a novel development for mathematical practices. However, this does not imply questions of truth and falsification, but questions about the individual/collective (and perhaps subjective/objective) transition points.

Symbol Systems as Cognitive and Performative Hybrids

Without drawing the old demarcation line between the context of discovery and the context of justification, because the two cannot be separated, the diffusion of individual tools and their justification (adoption) by a community is not easy to explain. Chance, contingency, and the status of a researcher or institute, respectively, may play a role, but these factors do not allow us to articulate a philosophical explanation of the transition between the individual/collective and the subjective/objective spheres. For instance, the success of the programming language Formula Translator (FORTRAN)—which dominates scientific computing even today, at least in some disciplines—can be explained by referring to chance, contingency, and status. Introduced in 1954 by John Backus, FORTRAN was the first programming language and it was used in IBM 704 computers from 1957 onward (Backus and Herrick 1954). IBM 704 computers became widespread in science and with them Fortran. 'The general availability of FORTRAN was probably one of the most important aspects of its perpetuation' (Rosenblatt 1984, 39; Gramelsberger 2010, 141 et seq.).

However, these factors are important, but not sufficient to explain its overall success. The epistemic advantage of FORTRAN resulted from two factors. First, 'Probably the most important thing about FORTRAN has been its adaptability. […] FORTRAN has been able to keep up with the latest ideas in programming art' (Rosenblatt 1984, 40). Second, because the motivation of developing it was based on asking what could be done now to ease the programmer's job? Once asked, the answer to this question had to be: Let him use mathematical notations. But behind that answer [...] there was the really new and hard question: Can a machine translate a sufficiently rich mathematical language into a sufficiently economical machine program to make the whole affair feasible (Backus 1980, 131)?

Mathematics as a 'natural medium of expression' of scientists was closer to the needs of scientists than the then used machine language for instructing computers. Nonetheless, FORTRAN became the *lingua franca* for scientific computing. Furthermore, similar to Feynman diagrams there was strong resistance in the beginning from 'instructors' using machine language, and even 'dialects' of the new programming language appeared until the American Standards Association brought out a first standard for FORTRAN in 1966.

Adoptability by a community because of *adaptability* to their needs show that symbol systems like Feynman diagrams, FORTRAN, and also structural formulas in chemistry are not only cognitive hybrids, but are also performative hybrids of theories and instruments. The metaphor of a *lingua franca* captures this latter hybridity best. In her study of structural formulas in chemistry, Andrea Woody draws the conclusion that the connection between the visual symbol systems and their explanatory power 'is pragmatic, being dependent upon the particular aims of this community. Certain representations are judged to be successful by a community of scientists'. (Woody 2004, 790) Furthermore, she argues 'that disciplinary identity itself is formed largely through explanatory preferences' (ibid.) and, one can add, therefore through its *lingua franca*.

The epistemic advantage of a symbol system combined with its inherent explanatory power marks an important driver for the transition between the individual/collective and the subjective/objective spheres. This epistemic advantage has been analysed especially in terms of Terry Shinn's and Bernward Joerges' concept of 'research technologies' (Shinn and Joerges 2002; Shinn 2008). Shinn and Joerges understand a research technology as a *lingua franca* that allows 'access to many audiences and arenas' (Shinn 2008, 10). Sometimes, it can even constitute a new way of seeing and therefore a new sub-discipline, thanks to the epistemic advantage and inherent explanatory power opened up by the representational, imaginative and organisational—as well as adaptational–liberation a new symbol system offers.

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