THE INTERNATIONAL JOURNAL OF HUMANITIES & SOCIAL STUDIES

An Overview on Quantum Trajectories II: Visual Research Traditions

Yeuncheol Jeong
Assistant Professor, Daeyang Humanity College, Sejong University, Seoul, South Korea

Abstract:
In the actual practice of quantum mechanics, the visual tradition still actively invokes and provides many fruitful forms of modern quantum mechanical research; scientific illustrations and metaphors are still effective ways to motivate research ideas and further developments. In particular, through illustrative and metaphoric representations on quantum dynamical processes, the Feynman diagram and the 'quantum trajectories' are powerful cognitive and computational tools. To some quantum scientists, therefore, they offers a visual and intuitive advantage on understanding quantum processes themselves.

Keyword: *Bohmaian quantum mechanics, Feynman diagram, quantum trajectory, representations, illustrations, metaphors*

1. Visual Preference in Quantum Mechanics

At first, the choice between the Bohmian quantum mechanics and the standard one simply looks like a matter of personal opinion or individual preference. However, it should be emphasized that there is particular visual preference even in quantum mechanical research tradition and that some individual preference can eventually become a separate research tradition and then a scientific debate among different research traditions can occur. These situations will be discussed here.

In a sense, a scientist's individual preference regarding Bohmian quantum mechanics can be traced back to and associated with a long-cherished visual research tradition in science. Nevertheless, the visual tradition in physics in particular is supposed to be not very active under the Copenhagen interpretation which has dominated for many generations all the quantum mechanical research. However, in the actual practice of quantum mechanics, the visual tradition still actively invokes and provides many fruitful forms of modern quantum mechanical research; scientific illustrations and metaphors are still effective ways to motivate research ideas and further developments even under the standard quantum mechanics. In other words, although the standard quantum mechanics does not provide (in fact, prohibits) a direct visual understanding of quantum systems, physicists have never given up some intuitive metaphors and pictorial illustrations on representing quantum systems.

Let's take another look into the visual tradition of metaphors and illustrations used in science. Like notations and symbols in mathematics, metaphoric and illustrative devices in science may not seem to add any more additional essential virtues in explaining physical processes. Therefore, metaphors are often trivially understood as mere as ornaments, especially to those theoretical physicists who emphasize only mathematical formality as in the standard quantum mechanics. In contrast, Jordi Cat (2001, p.398) argues for the important cognitive role for metaphors and illustrations. In his view, our representation of nature and our understanding of it are closely related through our use of language, and thus our representation of the scientific method is linked to our conception of language. In other words, the way we understand our cognitive process constitutes "a pathway into a broader and richer philosophical conception of a science and scientific practice" (p.395) and "the basis for a conception of understanding in terms of unification and concrete modeling, or representation" (p.395). Consequently, "different metaphors give rise to different cognitive perspectives, different aims, questions and even different methodological and explanatory preferences" (p.396). In a sense, "important metaphors are 'theory-constitutive'" (p.397).

In this respect, the importance of visual illustrations in quantum mechanics deserves to be more deeply examined, despite the continued acceptance of the Copenhagen formulation. Under the Copenhagen or the standard formulation, as emphasized already, many classical insights into quantum phenomena are seen as mere crude approximations or superficial descriptions of quantum-mechanical processes. Thus, classical insights are said to be misleading in our understanding of sub-atomic processes and even lead to misunderstanding. However, since sophisticated quantum imaging instruments have become available in surface science, the importance of visual (instrumental) images of quantum systems finally seem to be getting more attention than ever as a powerful "intuition pump for thinking about, intervening on, and responding to nanoscale technologies"[1]. A visual illustration in quantum mechanics shows what happens when a quantum system evolves in time and what surprises it may offer, although the relevant mathematical equations are already well known.

For instance, a group led by Eric Heller and Robert Westervelt at Harvard has developed an electron-watching technique that relies on a scanning probe microscope (SPM) to image the flow of electrons inside nanoscale devices at cryogenic low temperatures (Westervelt *et al.* 2004; Topinka *et al.* 2001). Images of electron flow from the quantum point contact (QPC) are obtained by positioning a negatively-charged tip of SPM above the surface of the sample and simultaneously measuring the position-dependent conductance of the device. When the tip is positioned over areas with high electron flow from the QPC, conductance is decreased; whereas, when the tip is over areas of relatively low electron flow, conductance is unmodified. Thus, a two-dimensional image of electron flow can be produced. Similarly, the group also uses an atomic force microscope (AFM) to visualize a sample's surface atoms by dragging a sharp tip over the surface and monitoring the force between the surface and the tip, which can be as fine as a single atom (Weiss 2004).

To make measurements of electron flow, researchers have forced an electron gas to pass through a narrow 'electrically-defined' gap before they permit the electrons to spread out. Then, using the AFM tip, they imaged in two dimensions the electron flow across the narrow gap with remarkable precision (Westervelt *et al.* 2003). After Westervelt's experiments, Heller then built a computer simulation of the electron flow, based on classical and quantum mechanical (trajectory) calculations.[2] He produced 'artistic' images of rich and delicate 'branching patterns' of trajectories on which individual electrons follow over a bumpy surface of an actual device. In the process, they claim, they have made not only 'scientifically informed art', but also have "experimented with" the images. This art form becomes a form of 'experiment' when the quantum chemists, re-use the images to make further measurement possible. In a sense, they interact with the image to know beforehand what form of instrumental type and design are further required to make the next specific measurements. The images they made therefore are not just a collection of data points on a screen made by an ATF tip. Through additionally added features of color and trajectories connecting each point, the chemists then present a visual representation from those data points. On the other hand, those data points in turn as a whole visually surprise the chemists about what happens in the system and what to expect next time.[3] Theorists are now trying to understand the origin of those branching patterns of electron trajectories with further computer simulations (*IEEE Computer Graphics and Applications* (January/February 2002), p.4). For example, in Eric J. Heller's 'Gallery of Digital Fine Art', Electrons are launched and then form branch, travelling over bumps (http://www.ericjhellergallery.com/index.pl?page=image;iid=7).

2. Visual Illustration in Quantum Mechanics

Another example showing the important role of visual illustration in quantum mechanics is Richard Feynman's formulation of quantum electrodynamics through diagrams. The Feynman's formulation is much more commonly used by practicing particle physicists than are the more abstract but equivalent Schwinger-Tomonaga one. According to David Kaiser (2000, 2005), Feynman's scientific diagrams and illustrations (originally, merely a social convention) spread among large particle physics communities and were put to work in many situations, generating new ideas and further developments. Originally, Feynman drew simple stick-figure line drawings and explained how these diagrams could be used as a notational device of corresponding equations in a relativistic quantum field theory when the high-energy particle interactions are handled perturbatively. The diagrams served as a 'heuristic scaffolding,' a means of keeping track of higher order correction terms to solutions of less complicated situations in a visually and systematically concise way. The pictures were a form of symbolic bookkeeping, or diagrammatic techniques, emphasizing the strict one-to-one correspondence between each feature of the diagrams and each mathematical factor in the corresponding equations. The Heisenberg uncertainty principle yet fundamentally forbad any possible discussion of particles' trajectories in space and time. Thus, through scientific metaphor and illustration, the diagrams only provided a conventional and representational scheme with no intention of picturing actual particles' real interactions in space and time. In other words, they were not meant to be read as literal space-time trajectories of particles but rather as a shorthand pictorial device, or, a heuristic tool of scattering process in high-energy physics.

However, those illustrative conventions were continuously taught and practiced as a piece of the educational apparatus for studying elementary particle interactions and scatterings. By the late 1950s, full understanding on Feyman's diagrammatic method was assumed for all Ph.Ds in both theoretical and experimental particle physics. Eventually, the diagrams became an established visual tradition for treating elementary particles' propagation, interaction and scattering in

---

[1] Davis Baird in private communication.

[2] This can be done through the 'guidance condition.' Here, the standard time-dependent Schrödinger equation was first solved to get the wavefunction of a quantum system, and then the 'guidance condition' was tacitly introduced at the last step only as a 'heuristic tool' in visualizing the trajectory. Of course, physicists will be reluctant to do this due to the issues such as realism and determinism involved with an electron' trajectory. This may be one of the reasons why the condition was only tacitly introduced in the first place so that the (Bohmian) interpretational issues can be avoided. However, physicists may find it quite surprising that those quantum chemists and engineers are not very concerned about the dichotomy between realism and antirealism in describing quantum phenomena. The dichotomy itself is of little use considering the rich and diverse nature of the research activities. This particular scheme can be classified as a hybridization of Bohmian quantum mechanics within the standard framework.

[3] In his 'art' pieces, Heller embellishes the computer-generated branching patterns of trajectories with color, shading, and other effects by means of commercially available image-manipulation software. He started with Fortran code, or with MSC Software's Interactive Physics (IP), a set of tools for making physically realistic simulations in a 2-D plane, and he then applied color gradients in Adobe Photoshop to each electron trajectory to complete the landscape images. His works involve far more than applying a computational scheme to the time-dependent Schrödinger equation. His art pieces are prime examples of scientific illustrations or metaphors with which the scientist's imagination actively interacting with his practice of science.

all areas of high-energy physics, far more general than the limited roles they had been originally designed to play in a relativistic quantum field theory. Interestingly, some physicists even started to take the diagrams to be a definite physical picture of the process, much more than just a convenient heuristic device or notion. In this period, new detectors began to produce nuclear emulsion and bubble chamber photographs showing particles' trajectories, and these were at the same time published along with the stick-figure reconstructions of corresponding Feynman diagrams, elevating them to the status of visual evidence about real particles' actual behavior in space. Therefore, "the association of 'realism' with Feynman diagrams in the 1950s and 1960s, based on their simple similarity to 'real' photographs of 'real' particles, helped the Feynman diagrams to stand out for many physicists" (Kaiser 2000, p.75). For example, a bubble chamber photograph of negatively charged pi mesons can be directly compared with a Feynman-diagram-type reconstruction of the interactions such as in David M. Harrison's 'Physics Virtual Book Shelf' at the Physics Department of University of Toronto (http://www.upscale.utoronto.ca/GeneralInterest/Harrison/AntiMatter/AntiMatter.html).

3. Cognitive Importance of Illustrations and Metaphors

As both Heller's and Feynman's research shows, the cognitive importance of illustrations and metaphors cannot be dismissed as merely educational or ornamental tools. They occupy a central place in the course of research developments and, more importantly, in the course of presenting those developments to their professional colleagues who do not simply stand in for mathematical or even verbal descriptions. Scientific illustrations convey cognitive information for which verbal and mathematical descriptions have a limited capability of conveying a cognitive meaning.

In other words, these forms of representation perform diverse and unique cognitive (and social) functions to provide better understandings of the theories to the scientists themselves and also to their wider audience. According to Cat (2001), there is no predetermined single function for a given representative form. Thus, regardless of their ontological implications, their usages can be redirected, expanded, and re-appreciated from their originally intended meanings to cross disciplinary boundaries into different conceptual contexts. Those representative forms of scientific illustrations and metaphors can include [1] mathematical notations or formalisms, [2] illustrations, graphic models, and visual images, and [3] a whole body of metaphors and verbal analogies (Cat, 2001). Especially, when representative forms are consistently coupled together, they cover a variety of contexts in a given scientific model and give rise to a series of powerful constructive intuitions and further research motivations for the model. Eventually, they can motivate and suggest experiments. This is possible because the illustrative and metaphoric quantities could call to mind more concrete and clear conceptions of further experimental (and theoretical) developments (Cat, 2001).

However, the diversity and fruitfulness of representative devices in a given model does not guarantee its later success. Historically, on the contrary, there are episodes of eventual demise of a scientific model with a rich form of representation inside, which originally motivated enthusiastic and powerful intuition among the followers (such as the ether model). Nevertheless, to some scientists (and engineers), the intuitive or cognitive advantage those forms of representation provide can be the single most important motivation for their continuing pursuits of a given scientific model.

For example, a certain notation or a symbol is widely used to indicate a specific operation in mathematics. At first look, it seems to make no difference whatsoever whether a particular type of notation is adopted or not, as long as the same symbol is consistently used without confusion to refer to a designated operation. So, there is a widespread conception that a notation or a symbol is nothing but a socially-agreed upon convention. Many thus believe that it does not convey any other possible aspects of the operation involved. In the history of mathematics, however, this does not always prove to be the case. The way a particular operation is denoted can play a rather important and sometimes critical role in understanding and developing the operation itself, especially when the meaning of the operation was less well known or understood by a community. Thus, having a different kind of notation for allegedly an identical operation can end up providing totally different directions in understanding various aspects of the operation itself. Later, it could lead us to a better and further development of the operation.

Here is a particular example in mathematics for the two different kinds of notations. Two separate notations were developed for the allegedly same derivative operation in the early history of calculus; the Newtonian notation with 'a prime symbol' and the Leibniz notation with 'dy/dx' symbol. It turns out, with the dy/dx symbol, mathematicians can develop more effective integration techniques (for example, a U-substitution method) and an explicit way to indicate a derivative with respect to other independent variables (for example, a usual x-derivative as dy/dx, or a time derivative as dy/dt), thereby providing an easier notational extension to a partial derivative and a differential equation. All first-year-college text books of calculus emphasize that this Leibniz symbol, although historically ignored by the Newtonians, was a lot more than just a convention or a notation. It gave a cognitive advantage to a whole generation of mathematicians, and thus, worked as a conceptual framework for later developments in the following history of calculus.

In her discussions on several advantages of semiclassical models with visual or pictorial power at their disposal, Alisa Bokulich (2008, p.112) also emphasizes that the treatments with the visual representational devices (such as visual illustrations and metaphors) can be [1] an investigative tool "to investigate physical domains that might not yet to be accessible either experimentally or with a fully quantum approach," [2] a calculational tool "less cumbersome than full quantum mechanical calculations,"[4] and [3] an interpretative tool to "offer physical insight into the structure of a problem, in a way that a fully quantum-mechanical approach might not."

In a very similar way, through illustrative and metaphoric representations on quantum dynamical processes, Bohmian quantum mechanics (especially, the 'quantum trajectory method', in particular) shares all those advantages mentioned by Bokulich. The trajectories are a guiding light for a visual direction of the probability density propagation and are powerful cognitive and computational tools. To some quantum chemists and engineers, therefore, the Bohmian trajectory model becomes an effective and pragmatic middle path to accommodate both quantum and classical physics and offers a visual and intuitive advantage on understanding quantum processes themselves. With particle ontology and visual trajectory, the Bohmian models can thus extend classical causal intuition into the semi-classical domain, while they successfully take care of all genuine quantum effects.

4. References

1. Bokulich, A. 2008. Reexamining the Quantum-classical Relation–Beyond Reductionism and Pluralism. Cambridge: Cambridge University Press.
2. Cat, Jordi 2001. On Understanding: Maxwell on the Methods of Illustration and Scientific Metaphor. Studies in the History and Philosophy of Modern. Physics 32: 395-441.
3. Kaiser, D. 2000. Stick-Figure Realism: Conventions, Reification, and the Persistence of Feynman Diagram, 1948-1964. Representations 70: 49-86.
4. Kaiser, D. 2005. Drawing Theories Apart: The dispersion of Feynman Diagrams in Postwar Physics. Chicago and London: The University of Chicago Press.
5. Topinka, M. A. et al. 2001. Coherent Branched Flow in a Two-dimensional Electron Gas. Nature 410: 183-186.
6. Weiss, Peter. 2004 An Electron Runs Through It: Surprising Rivulets and Ripples Complicate the Microchip Picture. Science News. 166 (25-26): 394-396.
7. Westervelt, R. M. et al. 2003. Imaging electron waves. In International Symposium on Functional Semiconductor Nanosystem (Nov. 12-14) Atsugi, Kanagawa, Japan.
8. Westervelt, R. M. et al. 2004. Imaging Electron Waves. Physica E 24: 63-69.

[4] However, it can be claimed that the current-day semi-classical approaches are ironically getting more complicated than full quantum mechanical ones. One of the main reasons of this situation is due to the fact that the standard quantum mechanics and classical mechanics do not truly overlap to each other in mesoscale domain.