19th-century microscopists researching at the limits of instrument-aided vision assessed their research tools with »difficult« diatoms and other test objects that were not fully known to them. Not until new types of microscopes became available, whose powers considerably exceeded the light microscope (notably the electron microscope), could this uncertainty be removed. But this vindication was obsolete precisely because new, more powerful technologies had become available. In 1947, for instance, the author of an article on diatoms motivated his investigation with the remark that the diatom *Amphipleura pellucida* had »frustrated the efforts of some of the best microscopists for the last seventy-five years«.[6] He had thus set out to clarify the structure of that diatom with the help of the electron microscope. In a sense, the best validation of light microscopes could be obtained only when it was no longer needed. And of course, the very trade-off between epistemic gain and risk repeated itself with the electron microscope.

Jutta Schickore

6 J. E. Nielsen, »Electron Microscope Reveals a Possible Valve Structure of *Amphipleura pellucida*,« *Transactions of the American Microscopical Society* 66 (1947): 140–143, on: p. 140.

→ Axolotl → *Paramecium*

Electron

Over the years I have profited greatly from Hans-Jörg's writings. My latest engagement with his work has been through an unpublished piece of his on visualization, where he suggests that »making visible something that does not manifest itself directly and therefore is not immediately evident – that is, does not lie before our eyes – is the foundation and at the same time the foundational gesture of the modern sciences.«[1] Proceeding from this insightful remark, I would like to cast an eye on the visualization of the electron in early 20th-century experimental physics. My focus will be the visual rhetoric that the American physicist Robert Millikan deployed in presenting his oil-drop experiments to various audiences, both within and beyond the confines of the physics community.

In thinking about Millikan's achievement I have found particularly useful Hans-Jörg's notion of »schematization«. Schematization is an aspect of modeling practices and concerns the representation of hidden mechanisms via a »graphical imagining on paper« or, I would add, in the »mind's eye«. This type of visualization is often associated with high-level theory. For instance, the literature on visualization in early 20th-century physics has focused on the development of the theory of atomic structure during the 1920s. Several historians and philosophers of science (e. g., Arthur Miller, John Hendry, Henk de Regt, Arne Schirrmacher) have described the growing hostility among early 20th-century physicists towards the visualization of the behavior of the electron within the atom, while noting the persistence of visual imagery, especially in physics textbooks.

Schematization, however, also abounds in experimental science, in the form of iconic representations of experimental entities and their behavior. As regards early 20th-century physics, prominent experimentalists, such as Millikan, visualized electrons at the very same time this possibility was being attacked by theoreticians.

With a few notable exceptions (e. g., the studies of Gerald Holton, Peter Galison and Alexi Assmus, and Richard Staley), the issue of visualization in early 20th-century experimental physics remains a little-studied topic. The case of Millikan indicates the significance of this issue for understanding early 20th-century experimentation in sub-atomic physics.[2]

1 »Making Visible: Visualization in the Science – and in Exhibitions?«, manuscript dated 29/4/2009, p. 1.
2 For what follows, I'm indebted to Gerald Holton's pioneering and insightful study of Millikan's work. See

As is well known, Millikan's systematic observations of charged oil drops, moving under the simultaneous action of gravity and an electric field, enabled him to measure the charge of individual electrons. Millikan found his experiment »to be as interesting and as exciting as trout fishing.«.[3] From 1909 onwards, his meticulous measurements established that electricity has an atomic structure and provided »[t]he most direct and unambiguous proof of the existence of the electron.«[4]

In his entry on the electron in the *Encyclopedia Britannica* (1947), Millikan indicated that the issue of visualization was involved in the design of his experiment and, in particular, in the choice of his experimental objects, namely »minute droplets of oil«. One of the reasons that these oil droplets were chosen was that »they were as minute spherical bodies as anyone could ever hope to obtain and still have them visible; so that the changes in the force exerted upon them by a constant electrical field could be accurately measured«. By tracking the motion of an oil droplet, one could infer the number of electrons that it picked up (or dropped off). Millikan claimed, in a colorful rhetorical style, that »the number of units (*electrons*) on the drop at any time can be counted by the foregoing process with quite the same certainty with which we can count our fingers or toes«. Furthermore, »anyone who has seen the foregoing experiment, and hundreds, perhaps thousands, have now done so, has proved for himself the existence of the electron with just as much certainty as if he had seen it as a visible object«. Thus, »visibility« had for Millikan the status of a criterion of existence. Furthermore, he admitted that electrons *per se* were not visible; only their putative effects on the oil drops they were attached to could be seen.

In his *Autobiography* (1950) Millikan made the far stronger claim that his »apparatus […] represented a device for catching and essentially seeing an individual electron riding on a drop of oil«. Still, the qualification »essentially« indicates that what one saw was not quite the electron, but only the effects of its presence. This reading coheres with some of Millikan's other writings. For instance, in *The Electron* (1917) he pointed out that the limitations of our eyes preclude the observation of molecules (let alone electrons), whose existence is established only by the »mind's eye«.

I could go on quoting passages from Millikan's works, especially the more popular ones, where he uses the expression »seeing electrons«. To mention one more striking example, in *Time, Matter, and Values* (1932) Millikan presented his experiment as »practically equivalent to seeing one individual electron. The observer does not see the electron's legs move as it springs on or off the droplet, but he knows just as well as if he did see the electron itself the exact instant at which it jumps on or off by the instantaneous change in speed produced by that act«. Notwithstanding the anthropomorphic metaphor of the »electron's legs« (!), it is clear from the two qualifying expressions (»practically equivalent« and »as if he did see the electron itself«) that Millikan understood that all he could see was the effects of the electron's acts. The latter, on the other hand, could only be visualized by his mind's eye.

Furthermore, Millikan's rhetoric was not always consistent. While he often claimed that electrons could be directly inspected, he also admitted that electrons could not be seen at all. As for myself, I can think of only one plausible way to make sense of Millikan's experiment. What he observed was the putative effects of electrons, as manifested in the behavior of oil drops. What he visualized with his mind's eye was the particular mechanism via which those effects were brought about (i. e., particular electrons jumping on and off particular oil drops). Be that as it may, I hope to have indicated how fascinating the topic of visualization in early 20th-century experimental physics is. Hans-Jörg's inspiring work on visualization could very well provide a fruitful framework for investigating this neglected topic.

Theodore Arabatzis

→ Fireflies → Interactome → *Mus musculus fluorescenses*

his *The Scientific Imagination: Case Studies,* Cambridge: Cambridge University Press, 1978.

3 Robert A. Millikan, »New Proofs of the Kinetic Theory of Matter and the Atomic Theory of Electricity,« *The Popular Science Monthly,* May (1912): 417–440, on: p. 433.

4 Robert A. Millikan, »The electron and the light-quant from the experimental point of view,« Nobel Lecture, 23 May 1924, in *Nobel Lectures: Physics, 1922–1941,* Amsterdam: Elsevier, 1965, pp. 54–66, on: p. 55.