# *Illusions, Ghosts and movies in the history of scientific instruments*

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*Indiciis monstrare recentibus abdita rerum*
(Horace, *Ars Poetica*, 49)

## 1. Introduction

In his career, Gino Tarozzi investigated for a short time the history of science from the point of view of scientific instruments (Tarozzi 1983, 1988b, 1989a, 1989b, 1989-1990). He looked at the transition from modern to contemporary science, stressing the difference between their conceptions of scientific instruments: contemporary science does not behave like modern science when explaining and describing reality on the basis of its observable physical properties. He showed that the role of instruments within a scientific theory and the epistemological background of the theory are deeply connected and that this connection defines different philosophical points of view about scientific instruments.

His research in philosophy of physics and on the issue of scientific realism prompted his interest in the history of scientific instruments. More and more, Tarozzi investigated epistemological and metaphysical implications of the empirical dimension of science (Tarozzi 1980a, Tarozzi 1980b, Tarozzi 2009), and in particular he widely addressed his study around the problem of measurement in microphysics (Tarozzi 1985b, 1992a).

More recently, Tarozzi explored theoretical questions connected to scientific cinematography, in particular regarding some movies on electron interference, showing how these movies allow us to see properties that are unobservable according to the standard interpretation of quantum mechanics (Sedda, Tarozzi 2010).

Such a result seems to indicate the possibility to consider in some circumstances movies as a particular case of scientific instrument. Such a proposal may appear very provocative, but there are serious reasons for considering it sensible. To examine the use of movies in scientific research, a clarification is needed of the concept of “scientific instrument”, i.e. what an instrument should do and what we expect from it. I believe that the inclusion of cinema among scientific instruments requires not only a historical reconstruction, but also the endorsement of a peculiar epistemological position. The history of science must be evaluated epistemologically to shed light on the relationship between instrument and scientific theory and conversely, epistemology should be compared with historical data to see if in the past there were instrumental experiences similar to those of movies.

## 2. Measuring instruments in an epistemological history of science

Modern Science developed around the distinction and opposition between primary and secondary qualities. A large part of twentieth century historiography of science explained the transition from ancient to modern science in terms of the passage from a *qualitative* philosophy of nature, based on non-measurable secondary qualities to *a quantitative* philosophy of nature, based on measurable primary qualities. This kind of interpretation refers to a certain conception of science, based on experimental method and the mathematization of laws of nature, which considers the scientific instrument as “neutral” and able to grasp properties of natural phenomena in an unbiased manner.

Quantum mechanics has destroyed this conviction, due to the introduction of the perturbative nature of measurement processes. The latter can no longer be viewed as a recording, but must be considered as an interaction between measuring instrument and measured object. However, the idea of an impartial observation of nature was problematic even before the advent of quantum mechanics and signs of weakness in this idea already emerged in relation to Maxwell's demon ideal experiment and to the paradoxes of Zermelo and Loschmidt, as well as to the unorganized complexity of Boltzmann and its probabilistic solution (D’Agostino 1983, p. 180).

In relation to these problems, Tarozzi expressed an interesting point of view, according to which instruments in the “revolutionary” phase of modern science, as masterfully remarked by Shea’s contribution in this volume, and especially the new scientific instruments like telescope, microscope, thermometer, barometer, made it possible to explore nature in greater detail. However, when this phase concluded, the instrument was relegated to a subordinate position (Tarozzi 1983) with respect to the theoretical framework. Thus, its role appeared really minimal and in a certain sense the instrument becomes “transparent” when the theory has been elaborated. Two aspects of description in classical physical systems can justify this assumption: the macroscopic dimension of the investigated systems and the concept of ideal measurement implying a negligible interaction between instrument and physical object. However, the measurement of electricity intensity already requires a disturbance: when an ammeter is inserted in a circuit, it absorbs electricity, so we are not measuring V/R (where V is the potential difference and R the resistance), but V/(R+R'), where R' is the resistance of the ammeter. This means that even in classical electromagnetism the interaction between measuring instrument and measured object cannot be considered irrelevant anymore. Indeed, in pre-quantum physics these kinds of problem could be resolved by reducing the interaction or using non-perturbing measuring apparatuses, for example the Kelvin electrometer. This is not sufficient, though, to maintain the old idea that theory completely subordinates instruments.

Newtonian mechanics and generally all new science were considered not only empirically founded, but also able to describe the unique part of describable reality. The relationship between the birth of new science and its empirical dimension based on a systematic use of instruments has been widely studied by historians of science (Righini, Bonelli, Shea 2012; Gaukroger 2008, pp. 352-399), also in relation to the role of other empirical approaches, like alchemy and magic.

As a synthesis of the classical view of the relationship between instrument, observation and observer, Tarozzi proposed the following scheme (Tarozzi 1989a):

$S_m \rightarrow A \rightarrow O$,

where $S_m$ is the measured physical system, $A$ is the instrument, $O$ the observer, that has been introduced for its central role in quantum mechanics, even if it plays a completely passive role in classical physics. In the previous relation the interaction between $S_m$ and $A$ is negligible, due to the macroscopic dimension of the system. In this way, the physical state of the instrument is not modified during measurement, and observer $O$ can register the observed data without disturbance. The possibility of error, either related to imprecision and insufficient sensitivity of the instrument, or to inaccuracy and the incapability of the experimenter, can be reduced by improving the instrumental apparatus and repeating the measurements. However, there is no doubt about the fact that the goal of these procedures will be the acquisition of knowledge about the true values of properties of a "real" physical object. A mathematical theory of measurement does not exist in classical physics, also due to the lack of an accomplished fundamental physical theory and the existence of a plurality of different theories for mechanical, thermal, magnetic, optical, acoustic and electrical phenomena.

It is only with the advent of quantum mechanics as a fundamental physical theory unifying the two basic models (corpuscular and wavelike) of the second half of the XIX century, that a unique theory of interaction between physical objects and measuring instruments, regarded as a physical object, becomes possible.

During the XX century and thanks to quantum mechanics, the scheme must be changed as follows:

$S_m \leftrightarrow A \rightarrow O$ .

The interaction $S_m \leftrightarrow A$ is established by Heisenberg's indetermination principle and the role of the instrument is evidently far away from the classical idealization. The idea of a subordination of instrument to theoretical context is in this way rejected, leaving space however to the unsolved problem of quantum measurement, and to the anti-realistic perspective of the standard interpretation of measurement due to von Neumann.

## 3. A reality for ghost waves

The «incapability to provide a reasonable explanation to the behavior of the photon in the double slit experiment […] in the light of the complementary interpretation of the Copenhagen school» (Tarozzi 1984, p. 141), prompted Tarozzi to design experiments to confirm a realistic interpretation and refute the standard subjectivist interpretation of the wave function of quantum mechanics (Tarozzi 1984, 1985a, 2013; Auletta-Tarozzi 2004a, 2004b), which are discussed by Lupacchini and Auletta in the present volume. In more recent times he proposed an experiment with Gennaro Auletta (AT experiment) to overcome the alternative realism-antirealism, which seems able to discriminate between two different forms of realism: *scientific realism*, which considers the wave function concept as real, and *empirical realism,* which considers the predictable properties as real, according to the EPR principle of reality.

If experimental evidences were to confirm correlations predicted on the basis of the pseudo entangled state introduced in the AT experiment, then such a result would in turn confirm scientific realism. The reality of wave-function raises the problem of which "kind" of reality has to be conferred to such a wave. Perhaps the latter would have a reality of a relational kind, in the sense that it could be only in relation to other entities and to their properties. If on the contrary no correlation is found, empirical and local realism of EPR will be confirmed and quantum mechanics would be falsified. This second possibility appears less probable, in reason of the evidences against Bell's theorem (Tarozzi 1986, 1992b). The first possibility, corresponding to a confirmation of scientific realism, seems to be more plausible, but it implies that predictability does not confer reality and that the category of causality has to be reformed (Tarozzi 1996; Tassani, in this volume). In a short diagram:

| | **Scientific Realism** | **Empirical Realism** |
|---|---|---|
| **Reality about** | (Relational) Entities | Predictable (and detectable) Properties |
| **Field of reality** | Non local | Local |
| **Causality** | Strong causal principle | Weak causal principle |
| **Completion of quantum formalism** | Deterministic hidden variables | Probabilistic hidden variables |
| **Open question (if true)** | Which kind of the reality for the wave-function? | How to reformulate the QM without the superposition principle? |

*Table 1: Scientific and Empirical Realism*

The confirmation of a realistic interpretation of wave function would ban all other orthodox and not necessarily orthodox interpretations of wave-corpuscle dualism: (1) Heisenberg and Jordan's point of view regarding wave-particle dualism as a pseudo-problem, based on the limits of the ontology of classical physics; (2) Born's merely probabilistic and corpuscular interpretation, assuming that only particles without waves are real; (3) Bohr's complementarity principle, assuming that either waves or particles are real, but not both at the same time; (4) Schrödinger's perspective regarding wave-function as an ordinary physical wave and excluding the existence of particles.

## 4. In the middle of the fiction: quantum-movies

Recently, as I shall try to show, Tarozzi investigated the question of scientific instruments from another perspective: that of the relationship between art and science. A reflection on the role of artisans, painters, engineers and architects in the Renaissance is a classical and fascinating theme in the history of science. The study of linear perspective is perhaps the most famous and significant issue, and thereafter astronomers studied mathematical and geometrical rules to improve the use of telescopes and microscopes. Another example is provided by the role of tables, illustrations and images as vehicles of science. This use is attested already in Mondino de Luzzi (1270-1326) and brought to a higher level in Andrea Vesalio (1514-1564), in Giovanni Battista Hodierna (1597-1660) and later in Carl von Linneus (1707-1778). The profound link between art and science emerges above all during the Enlightenment in the early encyclopedias and books (Schatzberg 2012). Thus, the classic distinction between natural bodies and artificial products, that ousted artists from the companionship of the true scholars, finally faded.

However, in the nineteenth century, the professional and institutional integration between theory and practice becomes real, framed in a significant change: by the late nineteenth century, applied science replaced the older arts. Instruments, that were one of the main causes of scientific revolution in the seventeenth century, turn into technological systems in the twentieth century. Thereafter, the term "art" now refers expressly to something that has an aesthetic finality in itself. This substitution provokes the differentiation between the philosophy of art and the philosophy of technology (Baird 2004). Similarly, the social role of the old arts became more incisive if we consider technology as an evolution of arts. Thus, the old binomial science-art became rather the pair of binomials: science-art and science-technology (technique).

Tarozzi focuses his interest on the protagonist of the evolution of art as a form of mass communication during the last century, i.e. cinema, but neither to discuss the relation between art and science nor to make an aesthetics of cinema (Pezzella 1996), nor a philosophy of cinema or a film-philosophy (Wartenberg 2011), as in the perspective by H. Bergson (1859-1941) and G. Deleuze (1925-1995). Neither does he even want to be engaged in the discussion between continental and analytical philosophy of film (Botz-Bornstein 2014), or to inquire into the ontological structure of fictional objects developed in different perspectives (Meinong 2002, Cavell 1979, Doležel 1998).

Tarozzi's approach does not belong to any of these possibilities: his original purpose is to assess whether movie can be a useful tool inside the binomial science-technology, i.e. whether a film may be a useful tool to capture those properties of reality needed to develop a scientific theory: «the relation between moving picture and physical science is an issue of considerable conceptual relevance, which has not yet been adequately scrutinized, with the exception of some detailed analyses on the role of the technical applications of physical theories in the birth and the evolution of cinematography» (Sedda, Tarozzi 2010). Actually, cinema has been useful for scientific research: the best known examples are the running horse by E. Muybridge (1830-1904) or the falling cat by É.-J. Marey (1830-1904). Even more significant for the history of science is, at the end of the nineteenth century, the discovery of X-rays, a phenomenon not directly observable, but able to impress photographic emulsions. In these cases, photography and movie can without doubt be considered scientific instruments.

## 5. QM-movies as a scientific instrument

Almost a century later, the cinema, having meanwhile turned into the most popular form of art and mass communication, assumes once more its original scientific role. In 1974 the physicists Pier Giorgio Merli, Giulio Pozzi and Gianfranco Missiroli (MMP) realized a short movie at Bologna University (Merli-Missiroli-Pozzi 1976), in collaboration with Lucio Morettini and Dario Nobili, to show primarily how the interference phenomenon can be observed experimentally not only in the case of radiation but also in that of matter at the elementary level. The film was so successful as to be awarded the Prize for the Physics in 1976 at the VII *Festival International du Film Scientifique dell'Université Libre* in Brussels.

In the MMP movie, electrons arrive on the monitor of the electronic microscope, through the flashes of light left by their impacts, as well as the rapid, progressive creation of an interference pattern. The crucial part of the experiment is represented by the *observation*, or rather by the *vision*, of the single electron interfering with itself. This actually occurs in two stages: in the first, the source emits a beam of electrons and many simultaneous arrivals can be observed, together with the appearance of the interference pattern. One cannot speak in a strict sense of an electron's self-interference, since inside the interferometer many electrons are present at the same time. In the second part of the experiment, the source is sufficiently weakened, so that only one electron at a time enters the interferometer and we are therefore faced with an authentic self-interference phenomenon. Nevertheless, such a phenomenon appears in two slightly different times: at the beginning one observes no more than the flashes produced by single electrons on the monitor and only after a certain time does one begin to see the interference fringes, in such a way that the wave-like aspect does not occur contextually with the particle-like aspect.

Therefore, the mysterious dual nature of atomic objects in the ideal double-slit experiment discussed by Feynman is transformed by MMP into a real experiment that allows us to see for the first time directly with our eyes the electrons on the monitor: not the macroscopic virtual image formed on the old television's cathodic tube by an appropriate distribution of beams of electrons, but the very real image of the fundamental constituents of reality.

More recently, Akira Tonomura made pioneering contributions to the holographic electron microscopy and, with a one-minute movie, showed the appearance of interference fringes directly on photographic film (Tonomura 2005) and not on the monitor of an electron microscope as in the MMP experiment. According to R. Rosa, this new experiment did not contain any real element of novelty with respect to that of the Bologna physicists (Rosa 2008).

According to Tarozzi and Sedda, the difference between the two experiments consists in the fact that whereas in the MMP experiment particle and wave-like aspects of matter do not appear at the same time, in the Tonomura one there is a compresence of these two aspects.

Thus, cinema can illustrate the phenomenon of the interaction of a single electron with itself and therefore it represents an instrument able to explore the behavior of quantum-reality; an instrument that allows us to see the unobservable dualistic nature of microscopic phenomena. Moreover, this is possible thanks to two basic features that make cinematographic language a newsworthy instrument for scientific research:

1. The frequency of an image could be either increased for fast movements, highlighting the non-observable intermediate states of a process, or decreased to make overt slow motions;

2. The power can be microscopic to enlarge small objects, and telescopic to bring into view the optical instrumentation used, which distances objects.

## 6. Concluding remarks

We shall try to propose some further considerations. MMP and Tonomura movies can have not only a didactic use and value, but even something more. First, cinema certainly cannot be considered strictly a measuring instrument. However, measuring instruments do not always limit themselves to giving precise quantitative measurements. If one does not want to use examples from ancient science, when Heron's theaters and machines could be also experimental instruments, think of Francesco Redi's (1626-97) jars and John Needham's (1713-81) containers. In the latter cases the instrumental apparatus is not used to measure, but to observe otherwise non-observable "states": the objective is only "to observe" not to make measurements. Let us also think about the early vacuum tubes used to amplify electrical signals and in general, all the tools you need to amplify signals rather than to measure such as a simple acoustic amplifier or the electron multiplayer. Only at a later time, can you decide whether to intervene appropriately to make measurements, like Galileo, who applied the micrometer to the telescope. This leads to another consideration.

The filmic recording is always something visible, which comes under the sense of sight. In a way, it could be the direct heir of Aristotelian science, which was anxious to describe phenomena on sensorial data. Even in Newtonian science this is still partially true. Two icons express the enduring phenomenal character of modern science: the telescope, but also the microscope. In the *Sidereus Nuncius* Galileo did not give definite evidence to explain his *perspicillum* operations, but through it he saw something. First *video*, then *demonstro*. However, cinema can show us an accelerated or retarded reality, but also a stroboscope does the same and we have no doubt that the latter is a scientific instrument. Thus, on one side there is an object and on the other its representation. In some cases, the object itself is modified so that one can see its existence (as for instance with photomultipliers). In other cases, one already sees the object and accelerates the vision to observe even more about it (as in movies, or in an astronomic simulator). Reality or the perception of reality is altered with the goal to observe deeply reality itself. When an instrument alters the temporal dimension of a natural system, it could also report its "history". However, the purpose of cinematographic reproduction of images in the case of auto-interference of the electrons and its dualistic behavior is not explicative: in this case, it is not a form of "how we understand something", but of "how to see something". The acceleration creates the conditions to observe this "something": like some scientific instrument, which creates the conditions to observe something, what is seen would have a heuristic value.

Moreover, the theme of the unobservable is typical of twentieth century philosophy of science, connected with the problem of the relationship between an object and the track that it leaves: can this track be regarded as evidence of existence of the object? The problem could be addressed both in an ontological perspective, discussing how dispositions become properties, and in a methodological one. The first point of view would require a discussion too broad for the purposes of this contribution. Concerning the second one, let us remember that every scientific instrument has an "inherent limitation": i.e. it is prepared to see just what could be seen by that instrument, because it is able to detect parameters that are inside the theory in which that instrument is embedded (D'Agostino 1983, p. 179).

MMP and Tonomura's films bring dual-objects from unobservable-world to observable-appearance, from *conjectured-world* to *perceptible appearance*. Again, movie helps to *show* something, not to *explain* it. A *new* scientific theory and a *new* ontology would be necessary to understand what is behind what you see (Barrow, Davies, Harper 2004).

In any case, what we have above called "track" here might be called "clue". Indeed as in civil or criminal proceedings, where circumstantial evidences are not necessarily a *probatio minor*, but evidences capable of supporting the final judgment. Thus, a clue is a sign of something as in Horace's *Ars Poetica* v. 49: «*indiciis monstrare recentibus abdita rerum*».

Summarizing, the movies of MMP and Tonomura should be considered instruments precisely because they are amplifiers of the sense, reproducers of phenomena and detectors of unobservable behavior. In a more general sense, they are like a catalyst for clues.

A rejection of all this would force us to reject the very idea of using film as a tool. However, if so, one wonders if we do not run the risk of Cesare Cremonini (1550-1631), who foolishly refused to use the Galilean telescope, because in his opinion it did not reproduce the "true" reality. It is impossible to do science without giving an at least partial cognitive value to experience. I prefer to opt for a "non-Cremonini attitude", with the caveats that film shows and does not prove or demonstrate.

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