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On the Poietic Character of Technology

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ABSTRACT

Large part of contemporary science is in fact technoscience, in the sense that it crucially depends on several technologies for the generation, collection, and analysis of data. This prompts a re-examination of the relations between science and technologies. In this essay, I advance the view that we'd better move beyond the 'subordination view' and the 'instrumental' view. The first aims to establish the primacy of science over technology (or viceversa), and the second uses technology instrumentally to support a realist position about theoretical entities. I suggest that we should instead concentrate on how science and technology interact. This will reveal that technology has a poietic character, namely it actively partakes in the production of knowledge. But this poietic character can only be understood within the cognitive activity of scientific communities. Current research in molecular epidemiology, notably the projects funded within the 'European exposome initiative', serves as a motivation for such discussion and as an illustration of the claims made.

keywords: technoscience, poiesis, constructionism, distributed cognition.

1. Introduction: The Longstanding Tensions between Science and Technology

Philosophical reflections on the relations between science and technology lie at the heart of discussions about the nature of knowledge and of reality. This is no accident, since science is the place where knowledge (i.e. our understanding of the world) is 'produced', and technology has to do with instruments that we use to gain said knowledge, or that we craft using said knowledge.

Such discussions can be found—more or less explicit—in the whole course of Western philosophy (and probably Eastern too), starting from ancient

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Greece. In the following, I shall not provide a thorough historical reconstruction of the relations of science and technology, as this would be a much larger project, one that has been taken up by a number of scholars, albeit not with the same emphasis that I would like to give it (see e.g. Ficham (1993); McClellan and Dorn (2015)). Instead, I shall confine my discussion to two salient positions that I call, respectively, the 'subordination' view and the 'instrumental' view.

The subordinate, or ancillary, position of technology with respect to science started with the Greek conception of knowledge, science, and technology, which influenced much of the subsequent thinking. In Greek philosophy, *physis* indicates nature and reality while *techne* indicates creation of artefacts and practical (or applied) sciences. Studying the physis means, primarily, to observe it and to discover its 'truth', which is couched into demonstrable knowledge (episteme) or, even higher, intellectual intuitions (noesis). This is the sense in which, according to Aristotle or Plato, we acquire knowledge of first principles and of 'eternal things'. Techne has instead primarily to do with the production of crafts and artefacts; but there are also forms of practical knowledge that have to do with deliberation (phronesis) or with 'applied' knowledge such as the medical art, rhetoric, and even music. In these activities techne has a poietic power, but not an alethic power. Thus, episteme—i.e., knowledge—stems from our observation and representation of the physis, but not from the use of instruments. It is worth noting that, heavily inspired by Greek understanding of physis, techne, and truth, authors like Heidegger (1933), Bunge (1979), or Galimberti (1999) maintain that technology *too* 'reveal' or 'disclose' some truth and thus establishes a link between techne and episteme, that was not obvious in the philosophy of the Greeks.

The advent of the scientific revolution carried out profound changes in the methods to study reality and, consequently, in the relations between the scientist or, rather, the natural philosopher, and Nature. The 'Galilean' and 'Baconian' methods encapsulate what we nowadays call 'modern science'. Here, the scientist ceases to be a passive observer, waiting for Nature to reveal itself, and becomes a *maker*. The modern scientist intervenes and operates on natural processes: s/he performs experiments, builds machines, reproduces phenomena. It is also in this sense that Floridi (2011) contra-poses the 'User's knowledge' tradition to the 'Maker's knowledge'—a point that will be further stressed in section 4, when the 'poietic' character of technology will be

discussed. Historians of science have long emphasised the importance of experiments, machines, and of the 'workshop tradition' for Galilei's or Bacon's achievements (Machamer, 1978, 1998; Klein, 2008). Yet these historical examinations have not discarded the idea, still pervasive in a certain philosophy of science, that technology is but the 'maid-servant' of science: instrumental apparati are merely *at the service* of studying of Nature, but they don't have any specific role in the process of knowledge production, nor they raise any interesting epistemological question.

Contemporary versions of this subordinate view ultimately aim at restoring some kind of primacy of science over technology, arguing that without science, there is no technology. One such position is held by e.g. Arageorgis and Baltas (1989). It is worth noting that arguments flowing in the opposite directions exist and aim to show that without technology there is no science—see e.g. Hansson (2015). What seems to be at stake here is whether experiments come first, or whether theory does—a question that, according to Ian Hacking (1983) is ill-posed. Much philosophy of science, notices Hacking, is theory-dominated, downplaying creation and overstating discovery. Instead, following Hacking, it is important to note that experimental apparati are, in a sense, 'hand-made', and therefore we create scientific discoveries too. We create phenomena with experiments, not just discover them. Phenomena, he says, are difficult to 'reproduce' precisely because we have to create them, they are not out there easy to pick out.

This leads us to the second view, that I call 'instrumental': technology and instruments are central in the 'creation' of phenomena. The role of technology is now made central in order to support a *realist* position, also known as 'instrumental realism' (see Hacking (1983) or Ihde (1991)). Simply put, instrumental realism holds the view that technology enables better and deeper investigation of Nature. We can see smaller things with a microscope and bigger things with a telescope, the important point being: whatever we see is real, because technology enhances our capacities to observe and study Nature.

In philosophy of science, the debate on realism has been by and large polarised around the question of whether we can legitimately infer the objective existence of non-observable and human-independent entities (say, electrons), given the current status of our best experiments and theories, mainly in physics (for an introduction to the debates on realism, see Chakravartty (2015)). Transposed onto the domain of molecular biomedicine,

to be discussed later in section 2, a relevant question would concern the objective existence of genes, various molecules, or biomarkers. In the realism debate, however, the role of technology has been largely neglected, with the exception of the instrumentalist position just mentioned. Here, technological devices, for instance microscopes, provide reasons to believe in the objective existence of entities that we cannot see with the naked eye, even when measurements and observations are mediated through them. Thus, technology backs up a realist position (i.e., that unobservable entities are real) in a rather sophisticated way. In particular, Hacking (1983) emphasised the kind of expertise needed in order to see through a microscope, as this requires a fair amount of knowledge at the theoretical level (say, in biology or chemistry or other) as well as of a practice. So if we 'see' small things such as viruses and bacteria, it is not simply because the instrument make our sensory apparatus more powerful, but also because we have the right knowledge, expertise, and skills to do so. This is also known as the Sneed-Stegmüller thesis of 'entrance knowledge' (Sneed (1979); Stegmüeller (1976). For example, the interpretation of an X-ray by a radiologist is made possible by a long training that includes notions of anatomy, physiology, radiation physics, etc. These are considerations that, as we shall see later in the paper, become important for knowledge *production*.

In their own way, instrumental realists try to restore a balance between science and technology. Philosophers of science, instead, by and large neglected or underestimated role of technology in science, and discussed science in rather abstract terms, privileging discussions of theories rather than practices (on this point, see for instance Boon (2015)). Quite a different perspective has been instead taken by Hans Radder (2003, 2012). In particular, Radder (2012) develops a sophisticated view on scientific realism, which he calls 'referential realism'. Two issues, in particular, are relevant to our discussion. On the one hand, Radder expresses skepticism about the possibility of establishing 'independence claims' (i.e., claims about the objective and human-independent existence of unobservable entities). This is because most of the phenomena on which such claims are based do not occur 'naturally', but are *artificially* created in the labs, using machines, and in need of much theoretical interpretation. On the other hand, the kind of scientific realism of 'mainstream' philosophy of science aimed to 'locate', or identify, unobservable entities by 'carving nature at its joints'. Yet, as Radder notices, the location (and the nature) of the joints also depends on the carving tools

used by the epistemic agent. These ideas will find further echo later in the paper.

In sum, with ups and downs, or taking different perspectives, the relations between science and technology have always been part of philosophical reflections. Yet, preoccupations to draw clear boundaries, or even priorities, obscured more interesting and pressing issues. In practice the border between science and technology is getting more and more blurred, gradually disappearing. To be sure, some scholars even hold the view that the border between science and technology, or between pure and applied science, never really existed, but have been instead 'artefacts' of historiographic quarrels or of socio-political pressures—see e.g. Mayr (1976) and Douglas (2014) respectively. Thus, rather than working on what makes science and technology distinct activities or practices, an interesting question is to delineate the profile of the notion of technoscience, where science and technology merge. This, however, falls beyond the scope of the present contribution, and I refer the interested reader to other contributions that explore the historical roots of the notion in the work of French epistemologist Bachelard (e.g. Rheinberger (2005)), or its hybrid status between pure and applied sciences (e.g. Boon (2011)), its role in scientific experiments and theory (e.g. Hacking (1983); Radder (2003)) or its relations to science policy (e.g. Bensaude-Vincent (2009); Guchet (2011)).

In this paper, I discuss recent research in molecular bio-medicine as a paradigmatic case of technoscience, one in which technology and science deeply intertwine. 'Exposome research' attempts to understand how environmental factors, such as pollution in air and water, are linked to a number of diseases, for instance cancer or allergies, at the *molecular* level. The methods recently developed in this field are marking a radical change with respect to traditional epidemiology. In fact, while traditional epidemiology already established robust correlations between environmental exposure and classes of diseases, such analyses do not yet allow to understand *how* causality flows from one to the other. The changes that molecular epidemiology is marking are both at the conceptual level and at the methodological level. On the one hand, a new concept of exposure—the 'exposome'—is being developed. The exposome includes *external* exposure to e.g. chemical agents as well as *internal* exposure, namely what happens inside the body in response to the external exposure. On the other hand, molecular epidemiology uses

sophisticated technologies, and particularly 'omics technologies', to study the 'exposome'. Simply put, omics technologies allow the measurement and analysis of biological samples at different molecular levels. Omic technologies (supplemented with several other pieces of technology) are used to identify biomarkers of exposure, of early clinical diagnosis, and of disease, and thus to trace the development of disease from beginning to end. This will hopefully improve on our understanding of disease mechanisms, which in turn will ameliorate early diagnosis and prevention.

I therefore begin, in section 2, with a thorough presentation of exposome science. I introduce the concept of 'exposome' and explain why it is marking an important change in the conceptualisation of exposure, one that leads us to move from traditional epidemiology to molecular epidemiology; I present the 'European Exposome Initiative', their hypotheses and methodology and, mainly, the various types of technology employed in these projects. With this background I investigate, in section 3, what technology contributes to molecular epidemiology. I shall spell out this issue in terms of the role that technology plays in mediating our epistemic access to reality. In particular, I emphasise the role of technology in producing and analysing data, and in detecting signal. Finally, in section 4, I expand on an idea that will have emerged in the previous discussion: behind technologies there are epistemic *agents*. Thus, the 'poietic' role of technology to create, analyse, and interpret data–and thereby producing knowledge too–cannot be analysed independently of the epistemic agent, or rather the *communities* of agents, that produce said knowledge. This is not meant to reinforce anthropocentric views of science or of knowledge, but rather to emphasise how much we, epistemic agents, are embedded in the surrounding world that we study, and that includes technoscientific instruments. Technology is an integral part of this tangle and, consequently, the interesting questions to ask about the relations between science and technology are not who comes first (subordination view) or whether we can still be realist (instrumental view). Rather, the interesting questions concern the *interactions* between epistemic agents and technology.

Admittedly, this essay is more programmatic than systematic, hoping to open up new avenues for research. If, as conjectured in section 4, we need to rethink a number of concepts in the traditional epistemological toolbox, this is work that cannot be exhausted in just one paper, and not even by one philosopher.

2. Exposome Science

2.1. The exposome

Epidemiology studies the distribution and variation of exposure and disease in populations. Traditional epidemiology—here, specifically, environmental epidemiology—has long established correlations between environmental factors or hazards and numerous diseases. Molecular epidemiology studies the same thing, but at *molecular* level. It is marking a milestone change in the field because of new methods for exposure assessment. While the 'old' methods of traditional epidemiology established (roboust) correlations between categories of determinants and categories of diseases, molecular epidemiology shifts the level of exposure assessment down to the molecular level, and thus investigates the molecular basis of health and disease.

Translated at the molecular level, the question about the correlation between exposure and disease becomes: How to identify changes in our bodies at the molecular level due to levels of chemicals in e.g. air or water? The short answer to this question is: by tracking biomarkers. The National Institute of Health Biomarkers Definitions Working Group defined, already in 1998, a biomarker as "a characteristic that is objectively measured and evaluated as an indicator of normal biological processes, pathogenic processes, or pharmacologic responses to a therapeutic intervention" (see Strimbu and Tavel (2011)). There are various good candidates, for instance metabolites in blood, proteins, or features of gene expression. Later I describe the technologies that enable analysis of bio-samples at different molecular levels.

Exposome research rests on two main ideas. First, exposure is not just 'being in contact' with 'external' factors such as pollution. We need instead a broader concept—the *exposome*—that includes both the external and the internal exposure. The external component of the exposome is assessed by measuring the levels individual chemicals in e.g. the air we breath. These chemicals are in contact with our body and we can measure their impact studying biomarkers (of exposure). But the body is also an environment, as biochemical processes happen *inside* the body as a consequence of environmental exposure. Thus, the internal component of exposome is assessed by repeated measurements in bio-samples before and after the exposure, and at critical stages in life, looking for biomarkers of changes due to exposure (see e.g. Wild (2005, 2009, 2011) Rappaport and Smith (2010)).

Second, it is not just biomarkers that we need to identify, but their evolution, or *continuum*, from exposure to early clinical stages to disease development. Tracing this continuum, from early exposure to disease, will (hopefully) allow us to better explain disease mechanisms and to make better predictions about disease development. So the use of biomarkers is not just to provide a much finer-grained assessment of exposure to environmental factors, but also to understand the changes that such exposure triggers inside the body.

Exposome research is, in a sense, a reaction to the disappointment of 'genomewide association studies' (GWAS). GWAS managed to collect a lot of data, but they advanced our comprehension of many diseases less that we expected to. Genes, apparently, explain much less than we thought, at least *alone* (Manolio et al., 2009). The complex bio-chemical basis of health and disease suggests that we need to study exposure in depth, in its totality. Whence this new course in molecular epidemiology: *E*WAS, i.e. *exposome*-wide association studies, hold the promise for better understanding and prediction of various diseases (Rappaport, 2011; Lioy and Rappaport, 2011).

2.2. Projects in the 'European exposome initiative'

Exposome science has a great potential to illuminate our understanding of several disease mechanisms. Its prospects have been readily recognised by the European Union. In fact, a 'European exposome initiative' has been started, some projects have been already funded, and some others are currently ongoing. I now briefly present three FP7/H2020 projects part of the exposome initiative. I then delve more on methodological aspects, including the tools, i.e. the technology, used.

EnviroGenomarkers (Genomics Biomarkers of Environmental Health) has been funded within FP7, run between 2009 and 2013, and involved eleven partners from six European countries.[1] The objective of the project was to study, using biomarkers, the role of environmental agents for breast cancer and Non-Hodgkin's lymphoma, and for childhood diseases including allergy, neurological and immune diseases, and thyroid disruption.

[1] National Hellenic Research Foundation, Greece; University of Maastricht, Netherlands; Imperial College London, United Kingdom; Umeå University, Sweden; Istituto per lo Studio e la Prevenzione Oncologica, Italy; University of Crete, Greece; University of Utrecht, Netherlands; Istituto Superiore di Sanità, Italy; National Public Health Institute (KTL), Finland; University of Leeds, United Kingdom; Lund University, Sweden).

EXPOsOMICS (Enhanced Exposure Assessment and Omic Profiling for High Priority Environmental Exposures in Europe) is funded within FP7, runs between 2012 and 2016, and involves twelve partners from seven countries.[2] The objective of the project is to study the 'internal and external exposome' for exposure such as air and drinking water contaminants, in order to predict risks of disease (notably, asthma, cardiovascular disease, cancer, neurodevelopmental changes) at the individual level. Exposure and risk are assessed at different critical stages in life, which includes *in utero* exposure.

Helix (The Human Early-Life Exposome – novel tools for integrating early-life, environmental exposures and child health across Europe) is funded within FP7, runs from 2013 for four and half years, and involves thirteen partners from eight countries.[3] Helix aims to study the 'early-lifeexposome',namely exposure to environmental hazards that happens in preand post-natal stages until childhood (6-9 years), and to link this to major diseases (notably, growth and obesity, neurodevelopment, immune system).

In the following, I first present the hypotheses and broad research strategy of these projects and then the technological tools put in place to carry out the research.

2.3. Hypotheses and methodology

The underlying idea of exposome science is that, in order to understand the development of disease, we have to identify key stages of its evolution. In particular, we have to find the biomarkers of exposure, of early clinical changes, and of development of disease. Identifying such stages means to better understand the effects of exposure, the mechanisms of disease, and also to be able to make better predictions about the evolution and spread of the disease.

A peculiarity of exposome research is that it is data-driven, rather than theory-driven. More specifically, data generated for this research come from the use of

[2] Imperial College, King's College, University of Bristol, UK; Universiteit Utrecht and Universiteit Maastricht, Netherlands; IARC, France; Centre de Recerca en Epidemiologia Ambiental and CRIC, Spain; Ethniko Idryma Erevnon, Greece; Swiss TPH and Genedata, Switzerland; University of California, US).

[3] CREAL, Centre for Genomic Regulation, Sensing & Control Systems, Spanish National Genotyping Centre, Spain; Norwegian Institute of Public Health, Norway; University of Crete, Greece; INSERM and INERIS France; Bradford Institute for Health Research and Imperial College, UK; Vytauto Didziojo Universitetas, Lituania; VGGM, Netherlands; HYLO, Italy.

various technological devices. Epidemiologist Chris Wild explains the importance of technology for this research thus:

> The value of these technologies will primarily depend on whether specific environmental exposures are indeed reflected in the human body by altered levels of specific mRNA, proteins or metabolites. Will distinct signatures or fingerprints of environmental exposures be found across a broad spectrum of mechanisms of action? If so *these new technologies* may be in a position to permit a step change in the development of biomarkers of both exposure and effect. (Wild (2009, p.121), my emphasis)

A pillar of exposome research is the 'meeting-in-the-middle methodology', first theorised by Vineis and Perera (2007) and the further developed by Chadeau-Hyam et al. (2011). The methodology prescribes to finding the biomarkers of exposure, the biomarkers of the disease, and then find the overlap, that is the biomarkers that are in the middle and that can link exposure and disease. These biomarkers are mid-way in the causal link from exposure to disease, that's why we have to meet in the middle, exploiting data from prospective and retrospective studies.

Prospective studies provide information about pre-clinical biomarkers of some particular exposure being measured. Retrospective studies provide information about clinic conditions at the disease stage and that can be related to pre-clinical response exposure (assuming that such data is available). To meet in the middle also means that the biomarkers in the overlap will be those associated with the exposure and that are good predictors of the disease. Chadeau-Hyam et al. (2011) present a pilot study that used data from the European Prospective Investigation into Cancer and Nutrition (EPIC). Scientists performed a comparison of spectra of plasma samples between the following cases: 43 cases (24 colon cancer and 19 breast cancer) against 43 controls. The plasma samples of the cases had been collected about 7 years before cancer appeared. Such comparison made it possible for the researchers to list possible intermediate biomarkers linking exposure and disease.

While the idea is simple, its implementation is rather complex. There are in fact important and delicate design issues. For instance: when should we make the measurements after exposure? Or, how can we minimise false positive and false negatives? Crucially, the extent to which the results attained are exportable from the examined samples to all individual arises in exposome research too. Exposome science is setting up a challenging research agenda, for which multi- and inter-disciplinary competences are essential. For instance,

statistical analyses need expertise on the biology to be correctly interpreted. Likewise, the technology used in omics analyses needs insight from statistics, epidemiology, and biology.

2.4. The technology in exposome research

Exposome scientists expressed the promise and potential of omics technologies for finding biomarkers and establishing the 'missing links' between exposure and disease very clearly (Thomas, 2006; Vineis et al., 2009; Vineis and Chadeau-Hyam, 2011).

While clearly essential to their research, omics are not the only type or piece of technology used in this field. In fact, besides the omics, technologies like sensors, GPS in smartphones, and sophisticated statistical softwares are also used. As I shall discuss in more detail later, all these technologies together are needed in order to generate, collect, transfer, and analyse a huge amount of data. In turn, these are essential steps for the production of knowledge concerning the targeted diseases. The use of *all* these technologies is changing the landscape, in the sense that research crucially depends on technology. This goes much beyond the idea of 'seeing the smaller' or 'seeing the bigger' using microscopes or telescopes. This kind of research is essentially *technology-driven*. Without sensors and smartphones no data would be produced, without omics technologies there would be no molecular analysis of biosamples, and without statistics softwares there would be no treatment of big data coming from the other two. The essential role of technology in exposome science thus revitalises the old, and hotly disputed, question of the relation between science and technology. I now provide a brief presentation of these tools, and in the following two sections I discuss some epistemological implications of the technological component of exposome research. Some of these conclusions are more tailored to molecular bio-medicine, while others more widely apply to technoscientific practices also outside this field.

Omic technologies. 'Omics' denotes a whole set of technological devices to analyse human biological specimens such as blood or urine at the micro-level. Omics help with characterisation of internal exposome, that is what happens inside the body in response to exposure to environmental factors and to any other (internal) process that such exposure may trigger. Analyses of biological specimens with omics enable scientists to collect quantitative data on global biological response to environmental agents. Various types of

measurement are performed, for instance, at the cellular level, multiple external chemicals (metabolites) or profiles of normal biomolecules as they are configured under the influence of external environmental factors.

Omics aim to identify biomarkers of the effects of environmental exposure at the different micro-levels in the body. More specifically: metabolomics studies chemical processes involving metabolites; adductomics studies DNA adducts that bind to DNA, causing damages and mutations in the cell; epigenomics studies epigenetic changes on the genetic material of a cell; transcriptomics studis mRNA expression profiling; proteomics studies proteins, especially their structure and functions.

Omics technologies use different tools, or machines, to run the analyses, for instance: high-resolution analytical platforms such as liquid chromatography coupled to mass spectrometry and/or nuclear magnetic resonance spectroscopy. Simply put, liquid chromatography is a chemistry technique to detect the presence of chemicals in other chemicals. Mass spectrometry allows scientists to measure mass-to charge ratio in charged particles, often exploiting processes such as the ionisation of energy in molecules. Nuclear magnetic resonance spectroscopy also allows us to detect physical and chemical properties of atoms and molecules, exploiting the magnetic properties of atomic nuclei.

The science and the technology that make these machines work is extremely complex and we don't really need to go into the details. Vlaanderen et al. (2010) provides an accessible introduction to omics, and the portal http://omics.org/ provides useful information about resources on the technologies and softwares, but also conferences and projects.

Sensors and smartphones. A peculiarity of the newest project in the 'European exposome initiative' is the use of 'personal' devices to collect data about environmental exposure and also about individual life style and habits. Smallmedium enterprises (SMEs), partners in the aforementioned projects, designed particular devices that can record air pollution or levels of chemical in the swimming pool waters. These are, for instance, palm-size units that individuals can wear. Such devices are connected to their smartphones, so that transfer of the records to the scientists data bases is afterwards made possible. GPS and motion sensors record location of users, type of physical activity and accurate estimates of rate of inhalation. Other applications are currently under study.

Statistics softwares. Omics, sensors, and smartphones produce immense data sets on external and internal exposome, from which relevant information has to be extracted. Statistics, and more specifically statistics softwares, is an obvious choice to analyse large data sets. But 'standard' statistical tools, such as those that 'traditional' epidemiology uses, are insufficient. This is because high-throughput techniques (i.e., omics and sensors described above) generate high-dimensional data, for which new algorithms for analysis are developed. These require expertise from both bio-statistics and bio-informatics.

Such sophisticated softwares allow to calibrate measurements, i.e. 'polish the data' from possible measurement errors. They also seek the best combination of biomarkers that predict exposure, by combining data from retrospective and prospective studies (see the meeting-in-the-middle methodology presented earlier). These softwares can handle hundreds of thousands of predictors. They check potential correlations within the data, that would therefore hinder any (possible) causal conclusion. Statistical analysis of the targeted biomarkers are used to validate biomarkers of exposure. Cross-omics analyses are also performed in order to investigate common patterns (Vineis et al., 2013).

3. Data Production and Signal-Detection

In the light of the presentation of exposome research in section 2, the following question arises: What does technology contribute to molecular epidemiology? One way of understanding this question is in terms of the role technology plays in mediating our epistemic access to reality, and thereby contributing to building knowledge of given phenomena.

Technology mediates our epistemic access to reality in a number of ways. In order to grasp them, it is helpful to use the concept of 'data-' or 'technology driven research', as opposed to 'hypothesis-' or 'theory-driven research'. Theory driven research is, simply put, science as we have known it until today: one role of experiments is to test the cogency, validity, or coherence of a theory, which is previously formulated. This is of course an oversimplification: experiments can also serve other roles, and there isn't always a strict priority of theory (Hacking, 1983). But for our purposes such oversimplification will do. Technology or data-driven research, instead, establishes (or aims to establish) causal relations *in absence* of theory. This is an oversimplification too. We are far from being at the 'end of theory', as advocated by Anderson (2008), and

theory still plays an important role even in 'big science' (Pietsch, 2016; Russo and Vineis, 2016). Yet, in fields like exposome research, technology is doing something quite important in the whole process of knowledge production. To begin with, technology *produces* the data, and then it allows scientists to *analyse* them. Both are particularly important when we lack strong theories to back up some choices about experimental design.

Consider for instance the 'PISCINA study' (Kogevinas et al., 2010; FontRibera et al., 2010). In this study, swimmers in pools are exposed to water disinfection by-products, which are absorbed by the skin and also inhaled. The study aims to measure levels of these by-products to assess exposure to chlorination by-products in swimmers, short-term respiratory health effects, and genetic damage after swimming. To do so scientists hunt for the 'right' biomarkers analysing blood, urine, and exhaled breath condensate. However, how long after the exposure should we collect samples? The possibility of collecting different samples, of producing data about different omics-levels, and of making the corresponding statistical analysis, all rest on the use of the technologies mentioned earlier in section 2.4. The hope is that appropriate omic analyses will help improve biological theory. What is most interesting here is the *interaction* between technology and theory. In a similar vein, Leonelli (2014) makes the point that research *in silico* needs to interact with research *in vivo* in order to interpret the evidential role of the data collected.

It is worth emphasising that I'm not saying that powerful technologies will make the automation of causal discovery possible—this clearly remains unlikely (see e.g. Leonelli (2014)). What these powerful technologies can do is to create the data—likely, much more than we actually need—and then to *analyse* them. This certainly opens incredible new possibilities for discovery. But behind the machines, the softwares, or any any other piece of technology, there always is the (techno)scientist, or actually, *many* (techno)scientists. Put otherwise: the epistemic access to reality facilitated by technologies is *not* independent of the the epistemic agent. This idea is further developed in section 4.

In exposome research, the epistemic access facilitated by technology is not to 'see better'. Sensor data, omics machines, statistics softwares don't enable a better vision or anything. They extract numbers representing measurements or calculations (especially correlations) on such measurements. It is then the hard job of the scientists to extrapolate what these numbers mean, to reconstruct disease mechanisms, from exposure, to early clinical changes, to manifestation

of disease. This a place where instrumental realists (see section 1), while rightly bringing to the fore the role or technology, missed to identify the big change that they entail.

Let me illustrate this point through Ian Hacking's classic discussion of seeing through the microscope (Hacking, 1983, ch.11). Hacking explains that, for Maxwell, there is *continuity* of vision through instruments, and so the distinction between observable and unobservable ceases to hold. In an essay that became a classic, Grover Maxwell (1962) addresses the central question in the realism-antirealism debate, namely whether the entities that scientific theories refer to are merely 'convenient fictions' or whether they refer instead to 'real' objects. One argument he gives—and that is relevant to our discussion—is that it is not clear how we can draw a neat line between seeing an object with the naked eye or via an instrument such as microscope or a telescope. The objection that what we see through a microscope are shadows, images, but not 'corporeal', 'physical' things is, says Maxwell, weak. In fact, his argument goes, one could raise similar worries when observing physical things through spectacles or even through an ordinary windowpane: here too we experience distortions in vision due to e.g. temperature gradients, however small. So a microscope is but a medium that ensures continuity of vision, not differently from our normal glasses, or even light and air that make vision possible in the first place. Bas van Fraassen (1980), however, famously argued against this position, holding the distinction and supporting the usefulness of unobservable entities just insofar as they 'save the phenomena'. Interestingly, van Fraassen is ready to claim that we 'see' through a telescope, but not through a microscope. Hacking uses these two emblematic positions to add important layers of complexity. On the one hand, we don't simply *see* through a microscope, until we have learned how to use it; this clearly re-opens an old debate between praxis and episteme, but I won't address it here. On the other hand, we don't see through a microscope, but *with* it; that is to say, the practical experience of seeing is also accompanied with a rich theorising about what these 'things' are, what they are for, etc.

But the instruments used in exposome research do not restore any 'continuity' from the observable to the unobservable, nor do they allow a finer grained epistemic access to the unobservable, in the way described by Hacking. To begin with, some of the notions exposome scientists work with do not correspond to any unobservable entity. 'Biomarkers' are paradigmatic in

this respect. Biomarkers are largely constructed by cross-checking data that are generated by some machines and subsequently analysed using other machines. So what kind of ontological status should we give to biomarkers? Molecular epidemiologist Paul Schulte (1993, pp.14-15) describes biomarkers in terms of 'events' in the continuum from exposure to disease, and then warns the reader that, however, we might still ask different questions: whether a marker represents an event, whether it is an event which itself is correlated with the event under scrutiny, or whether it is a predictor of that event. The question about the ontological status of biomarkers gets even more complex if we consider that molecular epidemiology is not interested in finding biomarkers *per se*, but in understanding the continuum of disease development from early exposures, *via* biomarkers. Here, there seems to be an emphasis on processes rather than entities, which may shift the meaning of 'reality' from something essentially made of 'things' to something that is instead made of 'processes' (for a general account of process-based ontology, see e.g. Floridi (2008)).

Detecting the relevant and useful biomarkers and the meaningful correlations in the datasets is often described and explained in scientific contributions as 'picking up signal from noise'. Witness for instance leading scientists in exposome research:

> While classical statistical models to analyzing -omics data serve the purpose of identifying signals and separating them from noise, little has been done in chronic diseases to model time into the exposure-biomarker-disease continuum. (Vineis and Chadeau-Hyam, 2011, sec.4)

> From these two parallel analyses [statistical analyses], we obtained lists of putative markers of (i) the disease outcome, and (ii) exposure. These were compared in a second step in order to identify possible intersecting signals, therefore defining potential intermediate biomarkers. (Chadeau-Hyam et al., 2011, p.85)

So the question is not so much whether omic technologies and statistics softwares allow us to see the smaller. The question is rather whether analysis of data created with omic technologies allow us to detect signals that we can interpret as a *links* from exposure to disease.

This opens up new directions for a reconceptualisation of causality (as, arguably, the links scientists are interested in are *causal*). This falls beyond the scope of the present contribution, but the interested reader is referred to Illari

and Russo (2014, 2016) and Russo and Vineis (2016), where the problem is examined, especially from an informational perspective. The arguments developed in those contributions are specifically tailored to bio-medicine, and more work is needed to explore signal-detection in other areas, for instance in particle physics or simulation in social science.

It is worth noting that signal-detection, at least in bio-medicine, requires synergies from different disciplines, and it is not by chance that projects mentioned earlier in section 2.2 involve epidemiologists, biologists, statisticians, and computer scientists (philosophers, sadly, are not officially in the partnership). Technologies bring to the fore an essential aspect of these research projects: the collective and interdisciplinary effort of *creating* knowledge. This applies more generally to technoscientific practices and is explored next.

4. The Poietic Character of Technology

The discussion so far hopefully made clear that the interesting questions related to technoscience are not about who comes first, science or technology. It goes without saying that without science, the machines used to record levels of chemicals in air or water, to perform the omics analyses and the subsequent statistical ones, would not exist. It would indeed be interesting, from a history of science and technology perspective, to find out how fundamental science helped build the machines now essential to exposome research. It is plausible to think that technology and science interacted very much at that stage too. In section 1 and 3, I further suggested that the interesting issue is not a reformulation of realist arguments, because instruments do not merely give us 'more' access to reality, enhancing our sensory capabilities of seeing the smaller or the bigger. The attempt here is to shift the question from the instrumental value of technology for realist claims to its role in *knowledge production*. This is what I call the *poietic* character of technology.

The biomedical sciences, as well as physics or even the social sciences, are deeply embodied in technology. This is how we can learn, nowadays, about disease mechanisms, or about particle collisions. But this embodiment is also strictly related to another, too often neglected aspect: there is no science (nor technology) without a scientist or technoscientist, in short, without an epistemic agent. Epistemic agents create knowledge, and the knowledge they create in much of today's science wouldn't be possible without technology.

The interesting issue to investigate is, therefore, the *interaction* between pieces of technology and epistemic agents. In spelling out such interactions, I try to single out the *poietic* character of technology. This is not to reinforce an anthropocentric vision of knowledge. Rather, it is to emphasise that, as epistemic agents, we are embedded in the world, and technology (the instruments) is part of this tangle. Let me explain further.

The point becomes crucial from an epistemological perspective, as we cannot hold anymore positions where subject and object (the epistemic agent and the world) are separated, apart, and instruments hopefully make up the connection between them. These considerations are very much in line with the perspectival view developed by Roland Giere and with the constructionist epistemology developed by Luciano Floridi, which I both use to clarify my point, and that I integrate with views developed by Sabina Leonelli and Nancy Nersessian.

According to Giere, knowledge is *perspectival* in character. He looks for a middling position that

> [. . .] mediates between the strong objectivism of most scientists, or the hard realism of many philosophers of science, and the constructivisim found largely among historians and sociologists of science. (Giere, 2006, p.3)

In his view, knowledge depends on the perspective of the epistemic agent, as well as the instrumentation used and the social dynamics in which research takes place. Just as data don't speak for themselves (alas, not even under torture), technology is not a 'neutral' tool to study the world either. It is in this sense that Giere stresses that *instrumentation* is perspectival too. He says:

> Most observational data in the sciences is now produced by instrumentation, sometimes very complex instrumentation. I will try to show that the output of instrument is perspectival in much the way that color vision is perspectival. Here we can distinguish two dimensions to the perspectival nature of claims about the output of instruments. First, like the human visual system, instruments are sensitive only to a particular kind of input. They are, so to speak, blind to everything else. Second, no instrument is perfectly transparent. That is, the output is a function of both the input and the internal constitution of the instrument. Careful calibration can reduce but never eliminates the contribution of the instrument. (Giere, 2006, p.14)

But there is another aspect in perspectivalims that is of interest to us. Science is a cognitive activity and, especially, it is a *distributed* cognitive

activity. This means that knowledge bears not only on the perspective of the scientist, but on the perspective of the *community*:

> Consensus among scientists on a particular scientific perspective arises out of both social interactions among members of a scientific community and interactions with the world, typically mediated by complex instrumentation. (Giere, 2006, p.15)

This is echoed by Sabina Leonelli, who talks about the "distributed nature of understanding itself as a cognitive achievement of *scientific collectives*" (Leonelli, 2014). Leonelli acknowledges important similarities between her and Giere's views, but with one difference: while Giere explored the role of technology in human cognition, she wants to emphasise that the cognitive achievements are distributed across scientific *collectives*.

This last aspect (the collective) is picked up and developed—albeit in slightly different terms—by Nancy Nersessian (2005, 2008), who includes cognitive, social, cultural, and even *material* aspects of scientific and engineering thinking. She thus endorses an environmental perspective that allows her to focus on the *process* of cognition, rather than on the product. This is an important step to move away from positivistic philosophy of science and epistemology, that have by and large dominated the debate in the last decades.

Two elements emerging from the discussion thus far are worth scrutinise further: interaction with the world and instrumentation. These are spelled out in Luciano Floridi's constructionist view (Floridi, 2011). Just like Giere, Floridi is in search of a middling position, one that is between two extremes: (i) the world is objectively there, independently of the epistemic agent, and (ii) the world is totally constructed by the epistemic agent, or rather by the groups of epistemic agents that engage in some kind of activity (for instance, scientific research). The third position Floridi develops is largely Kantian in character and pragmatist (in a Peircian flavour), but it updates these views in at least two respects.

On the one hand, the way we know the world *also* depends on what the world is like. In a Kantian perspective knowledge *pre*scribes what the objects are, while in mainstream realist positions knowledge merely *de*scribes the objects. Instead, in a constructionist epistemology, knowledge *in*scribes reality with semantic artefacts (e.g., theories, concepts, etc.). On the other hand, instruments, technologies, partake in this 'inscribing'. Knowledge becomes

then strictly related to the making (poiesis) and to makers (epistemic agents). As Floridi writes:

> Any child who learnt by doing, any person aware of the fact that understanding requires much more than passive observation, any student trained in a lab or in a field, any engineer who ever designed an artefact, any scientist who ever ran an experiment or devised a simulation, any user who ever felt the need to know more about a technology than just how to enjoy it, any academic who realised that teaching is a great way of learning, and, in general, anyone involved in the business of information creation, refinement, transmission, and acquisition must have perceived, at some point, *that our ever richer insights into the nature of reality have their foundation in our practical and creative interactions with it.* (Floridi (2011, p.282-283), my emphasis)

But knowledge has also another important characteristic: it is distributed not just across the 'brains' of the scientists, but also across the instruments that scientists use—a point also made by Giere and Nersessian. Differently put, we are not the only and sole epistemic agents, as the 'fourth revolution' should teach us (Floridi, 2014). Technology has thus a 'poieitic' character in the sense that it participates in the production of knowledge, an activity that is not anymore exclusive prerogative of (human) epistemic agents. The question of an alleged subordination finally disappears: technology *partakes* in production of data, in their analysis, and thereby in their interpretation.

But once we grant technology such poietic character, we have to be simultaneously ready to revise several notions in our 'traditional' epistemological toolbox. The discussion earlier in section 3 pointed to the notion of causality and to the ontological status of biomarkers (and, by extension, of any unobservable entitiy), but most likely we need to revise as well the notion of process, entity, experiment, and—I concur with Floridi—even *knowledge*. He says:

> The time has come to be epistemologically heretical, to abandon a passive, mimetic, user-oriented perspective as to how we generate our knowledge of the world, and to join forces with some of the less orthodox thinkers in our philosophical tradition, in favour of a maker-oriented approach. Knowledge is not about getting the message from the world; it is first and foremost about negotiating the right sort of communication with it. (Floridi, 2011, p.284)

There are however more profound consequences. Contemporary cases of technoscience, such as projects in the European Exposome Initiative, should

be triggers to refashion the profile of 'traditional' scientists (biologists, physicists) as *techno*scientists, whose skills and competences in technology or engineering are an integral part of thereof. Contemporary technoscience provides an opportunity for setting up a research agenda that explores in detail the meaning and consequences of this, for instance developing methods and epistemologies for interdisciplinary research, designing training programmes for interdisciplinary students and researchers, and even making recommendations to funding bodies about the evaluation of interdisciplinary proposals. Interestingly, this hybrid figure of the technoscientist is not new a new phenomenon. I mentioned in section 1 that historical scholarship has already recognised the fundamental role of Galilei's artisan-engineering training, or of Bacon's experience in the workshop. It is perhaps high time to bring these considerations to the fore and submit them to a thorough and systematic discussion.

5. Conclusion

Exposome research studies the 'total exposure': *external* exposure to external factors, such as pollutants, and *internal* exposure, namely all the bio-chemical processes that take place inside the body as a response to the external exposure. This is an emergent field of research at the crossroad of epidemiology, biology, bioinformatics, and information and communication technologies. Exposome science marks an important step forward with respect to traditional epidemiology, that had already established the existence of robust correlations between environmental exposure and various diseases. Such a step forward concerns the methods, the conceptualisation of causal links, and (pending results of ongoing projects) the understanding and prediction of a number of diseases.

A peculiar aspect of exposome research is that it essentially relies on technology for the generation, the collection and the analysis of data. In section 2.4, I described the use of omic technologies, of sensor and GPS devices, and of statistics softwares. Without these technologies no exposome science would be possible. It looks like the line separating science and technology becomes blurred, to the point that it is worth asking whether this changes anything in more traditional ways of conceiving the relations between science and technology.

The relations between science and technology have been at the heart of the philosophical reflection since at least ancient Greece. By and large, in the philosophies of Plato or Aristotle, technology is given an ancillary position with respect to science. While science, *episteme*, aims to reveal *the truth*, technology, *techne*, aims at the production of artefacts. While the first is a *noetic* activity, the second is merely *poietic*. In the course of time, the Greek position has been smoothed in many ways, one reason being that technology has become more and more central for science. Modern science has increasingly more made use of experimental apparati to discover, understand, and even create phenomena. Yet, even more contemporary philosophical reflections try to draw a line to separate the two and, in particular, try to establish some form of priority of one over the other. This is what, in section 1, I called the 'subordinate view'. Philosophers like Don Idhe or Ian Hacking contributed to 'liberating' technology from such subordination. Their philosophies, however, move from a subordination to an 'instrumental view', because technology enhances our human sensory capacities to see the smaller or the bigger, and is thus a means to establish the reality of what we see with such instruments.

In section 3 and 4, I tried to shift the question from either demarcation or realism to the *interactions* between science and technology. Technology is, in much of contemporary science, essential to the production, collection, and analysis of data–for short, the whole process of knowledge production. Technology has, therefore, a crucial role in mediating our epistemic access to reality. In exposome research, moreover, technologies help us detect signals, which in turn is central to establishing causal links between environmental hazards and the molecular mechanisms of certain diseases. These considerations may give the impression that I pushed the argument towards a primacy of technology over science. But this is not the case. In fact, technology cannot do any of the aforementioned tasks independently of fundamental science and of a community of epistemic agents– the technoscientific community. This paves the way for a thorough reconsideration of our epistemological toolbox. Knowledge becomes relational, rather than representational; cognition is not located in one individual, but distributed across the whole community, which includes 'human' epistemic agents as well as artefacts and instruments, cultural values, etc. Thus the *poietic* character of technology, namely its capacity to actively participate in knowledge *production*, leads us to outline new contours of notions such as 'knowledge' or

'epistemic agent'. In turn, this may prove fundamental in training new generations of scholars (whether scientists or humanists) or to design appropriate evaluation methods and procedures for current and future research. The frontier is not just given by inter- or trans-disciplinarity, but also by the collective nature of research, which includes close interaction with technoscientific instruments.

Exposome research has served as a motivation for such discussion and as an illustration of the claims made. Yet, the issues raised in this essay are certainly not confined to molecular biomedicine and epidemiology, and further research should distinguish aspects that specifically apply to this field from those that apply, say, to technoscientific research in particle physics, and from those that are instead more general in scope. A *philosophy of technoscience* holds a potential for addressing questions that have been prerogative of philosophy of science *or* of philosophy of technology, thus missing what seems to be a most promising idea: the *interaction* between science and technology, not their separation.

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