About a Definition of Nano: How to Articulate Nano and Technology?

Sacha Loeve

Abstract: It is often assumed that 'nano' is merely a communication and marketing token. Our inquiry in a number of French laboratories in the field of artificial molecular machines resulted in a quite different picture: a number of researchers are concerned with the definition of nanotechnology. This paper starts from the attempts made by one of the leading figure in the field of molecular machines, Christian Joachim, to draw a clear demarcation between what is 'really nano' and what is not. Probing the epistemological basis of his strategy, we also underline its limits. As this definition is only focused on the prefix 'nano', it would benefit from being completed and enlarged by a definition of 'technology'. We argue that molecular machines belong to the realm of technology in Gilbert Simondon's meaning of this term: a genesis of individualized objects coordinating natural processes and human projects. Finally, this emphasis on the technological dimension of nanotechnology leads to ethical reflections based on the practices of nanotechnology rather than on their potential applications.

Keywords: *nanotechnology, epistemology, science versus technology, molecular machine, individuation*.

> "Nanotechnology's father figure is President Clinton, whose support of the USA's National Nanotechnology Initiative converted overnight many industrious physicists, chemists and materials scientists into nanotechnologists. In this cynical (though popular) view, the idea of nanotechnology did not emerge naturally from its parent disciplines, but was imposed on the scientific community from outside. As a consequence, nanotechnology is a subject with an existential crisis – is there actually any firm core to this subject at all, any consensus as to what, at heart, defines nanotechnology?" [Jones 2006]

> "Nanomaterials, nanostructures, nanostructured materials, nanoimprint, nanobiotechnology, nanophysics, nanochemistry, radical nanotechnology, nanosciences, nanooptics, nanoelectronics, nanorobotics, nanosoldiers, nanomedecine, nanoeconomy, nanobusiness, nanolawyer, nanoethics to

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> name a few of the nanos. We need a clear definition of all these burgeoning fields for the sake of the grant attribution, for the sake of research program definition, and to avoid everyone being lost in so many nanos." [Joachim 2006]

1. Introduction

The term 'nano' is in an awkward position: it concerns more and more research fields and even refers to nature, its use increases dramatically and pervades common language. As it is being oversold, denounced, and discussed on innumerable websites where images of the nanoworld proliferate, it first sounds like a scientific marketing term. To many scientists, 'nano' is just a magic prefix to get funds and a way to communicate. Thus, they often deplore that the debate is too 'politicized'.

We contend that it is essential to go further, because in this situation, anything and its contrary can be said, from 'everything is going to be revolutionized' to 'nothing is new' – which triggers cynicism and complacent acceptance. Beyond the general views, we should show more interest in the objects, patterns, and knowledge the term 'nano' embraces, and most of all in this new situation: instrument-based relations to matter are moving out of the laboratory to be dragged to a public level.

A recent review of nanoscale sciences and technologies in the social and human sciences (SHS) points out that the issues of what is about to become a research field on the ethical and social implications of nano will remain too vague as long as (Kjølberg & Wickson 2007):

- significant applications of nano are still largely hypothetical and futuristic,
- there is no consensus on the definition of nano,
- there is no consensus on how to distinguish (or not) between nanoscience(s) and nanotechnology,
- there is no consensus on the dimension of novelty in the concerned practices,
- only 10% of nano-based literature directly concerns 'science', *i.e.* analysis of practice and knowledge,
- even without directly dealing with it, only 20% of the literature shows any concern on the matter.

This paper argues that it is crucial to share nano-objects and to discuss their values. If the nano-objects considered by SHS scholars have nothing to do with those of nanoscientists, it will be difficult to build mutual trust. 'What you say about nano has nothing to do with what we are actually doing, so we are not concerned. If this is your understanding of nano, then we can as well say that we are not doing nano', some nanoscientists did claim. If nano has no epistemic and/or technological ground, the discussion of its ethical impacts will always be problematic. Of course, the purpose of ethics is not to give consensual answers but rather to move into the depth of questions. It should therefore remain problematic, but in a reflective and explicit way. Sharing nano-objects does not mean seeking a consensus. On the contrary, this paper gives prominence to divergence.

2. To Be Or Not To Be… Nano

In the 'nanoworld', Christian Joachim belongs neither to the enthusiasts nor to the skeptics, but to 'purists', showing a great concern to the definition of nanotechnology. He means to distinguish clearly "what is nano from what is not" (Joachim 2005).

> Nanoscience should be reserved solely for the study of a single atom or a single molecule, that is, of one entity at a time, and not for groups of such entities where statistics or interactions between them come into play. [*Ibid.*, p. 107]

> The adventure of nanotechnology started with the molecule acquiring an existence of its own, as an independent material entity. [Joachim & Plévert 2008, p. 65]

Unlike the official definitions referring to the scale of 10^{-9} m that makes new properties emerge, Joachim's one is based on the individuation of objects, the scanning tunneling microscope (STM) allowing to manipulate them one by one. Joachim calls this approach *the nanotechnology*, as opposed to *nanotechnologies*. He contrasts his definition with a 'sociological' one that is too wide to convey right depictions of nano-objects. Bit by bit, he says, the scientific community has learned to disguise their projects in order to make them look 'nano'. According to him, 90% of these researches "are not actually nano" (Joachim 2005, p. 109). To Joachim, it is "a case of embezzlement" (Joachim & Plévert 2008, first chapter's title), a "political hijacking" by the US National Nanotechnology Initiative (NNI) in 2000 (*ibid.*, p. 15) of a project which was, in its very beginning, a fundamental 'ecotechnological' one (*i.e.* using the minimum amount of matter and energy sufficient to make machines).

Yet posing an 'original nano' well defined before 'the Fall' – the launch of the US NNI – is nothing but rewriting history. In the 1980s, there were many potential forerunners, protein engineering, supramolecular chemistry, ultrafine particle engineering, surface science, thin film engineering, mesophysics, molecular electronics, and scanning probe microscopy, but there was nothing like a well-defined ‘nanoproject’. The many candidates to the title make Joachim’s claim of a ‘pure’ origin in molecular electronics extremely doubtful.

However, we should consider seriously the *concern* motivating such a claim: as long as nanotechnology is shaped by futuristic objectives, non-historical claims, and purely conventional definitions, research communities who are trying to construct their ‘nano-identity’ need to dig into the past on their own to construct ‘counter-histories’.

3. Big naNNo and Small naNo

Christian Joachim has a nice way of distinguishing ‘real nano’ from ‘fake nano’. The word meaning dwarf was occasionally spelt ναννοσ with a double ‘n’ in ancient Greek and *nanus* with a single ‘n’ in Latin. The term reappears in the 19th century. In 1960, the eleventh General Conference on Weights and Measures decided that Latin would be used to qualify the fractions of the meter (*e.g.*, milli-, micro-, pico-) and that Greek would be used to qualify the multiples of the meter (*e.g.*, mega- and giga-). It was therefore necessary to designate the unit 10^{-9} with a Latin term rather than with a Greek one. That would explain why ‘nanno’ has become ‘nano’.

Beyond the linguistic quarrels, this story matters to Joachim because it allows him to distinguish his practice from the ‘big nano’: to him, what we call ‘nano’ today is in fact ‘nanno’ when it comes to the mesophysical (intermediate) scale. It would have been more correct to use the term ‘nano’ for objects of a few nanometers and to keep the term ‘nanno’ for that intermediate scale. What matters in this definition is not size but the difference between the *statistical* approach and the *individual* approach to phenomena. Electronic, optoelectronic, and spintronic devices that show quantum phenomena but are analyzed statistically concern mesoscopic physics; the same is true of macromolecular machines in biology – kinesin, myosin, ATP synthase, *etc.* – which are treated classically with some stochastic ‘noise’ and statistical ‘fuzziness’. On the other hand, monomolecular machines are made up individually through internal quantum behaviors intervening with a single object (a molecule) or a few countable objects (electrons) rather than in a statistical way. To Joachim, confusion has eventually been established and ‘nano’ has come to qualify any object of nanometer size. Joachim’s definition of nanotechnology excludes much: microelectronics (whose components are engineered to the precision of few nanometers and which are nanoscale objects); biochips and microarrays, which are considered tools whose functional elements are ultraminiaturized rather than being specific molecular objects;

nanomaterials (materials whose macroscopic properties are controlled at the nano-scale); and nanoparticles (assemblings of atoms with at least one dimension less than 100 nm). It also ignores plastic electronics as well as 'hybrid' molecular electronics, and argues in favor of monomolecular electronics, considering the molecule a circuit component or a whole circuit (Joachim, Gimzewski & Aviram 2000).

4. Nano and Meso

Joachim points out a striking amnesia: it is no accident that mesoscopic physics is barely heard of anymore. It is not because it is obsolete or outdated, but because the whole 'meso' field has been renamed 'nano'. At Bell Labs and IBM, mesoscopic physics referred to the *physics of ultrasmall devices*, linking it to a very precise engineering problem: that of the *physics of non-ohmic conductors*, *i.e.* conductors that could not be modeled as ohmic conductors.

An ohmic conductor is an 'ideal' or a 'pure' conductor that perfectly follows Ohm's law (U [volts] = R [ohms] × I [amperes]), because R remains constant whatever the conditions of use. Yet no dipole is perfectly ohmic because the resistance is responsible for heat dissipation through the Joule effect. An ohmic conductor therefore does not exist; it is an ideal object used for modeling real dipoles. However some dipoles with so-called 'fixed' resistance capacities come close to Ohm's law, statistically speaking. Double N-P-N and P-N-P junctions allowed making the famous bipolar transistors, replacing the vacuum tubes in the 1950s. Later, thanks to the silicon n-doping (excess of electrons) and p-doping (excess of holes), semiconductors in microelectronics approached even more the ideal conditions of ohmic conduction. They allowed to control almost perfectly the value and the direction of the current and to obtain constant resistances. Thanks to the doping process (along with other measures), the heat dissipation and therefore the increase of the system's general entropy could be neglected. And yet when the size is diminished, new problems occur because the conductor's non-ohmic features have to be taken into account explicitly (Landauer 1961; Bennett 1982, 2003).

Mesoscopic physics studies the properties of systems at the quantum-classical interface. As is noticed in a subtle and precise study on the definitions of nanotechnology (Schmid *et al.* 2003), the definition of mesoscopic physics overlays many current definitions of nanotechnology. The study quotes S. Datta's definition:

> Small conductors whose dimensions are intermediate between the microscopic and the macroscopic are called mesoscopic. They are much larger than microscopic objects like atoms, but not large enough to be 'ohmic' […]. The length

> scales vary widely from one material to another and are also strongly affected by temperature, magnetic field *etc.* For this reason, mesoscopic transport phenomena have to be observed in conductors having a wide range of dimensions from a few nanometers to hundreds of microns. [Datta 1997, pp. 1-2]

Indeed, according to Datta, mesoscopic physics refers to conductors whose dimensions are in the order of (1) the de Broglie wavelength associated with the kinetic energy of the electrons, (2) the mean distance covered by the particles before collision *(mean free path)*, (3) the distance an electron must cover to cause a system to relax or return to neutral (*phase relaxation length*). Mesoscopic physics uses the very dimensions mentioned in the official nano definitions (1 to 100 nm). Van Kampen (2007), who was one of the inventors of the term 'mesoscopic', gave a definition that tallies with Joachim's – mesophysics, Joachim says, encounters quantum behaviors that interferes with determinist laws but that are still analyzed statistically.

Therefore, Joachim legitimately insists on distinguishing his own research from the 'meso' approach. The quarrel is thus also epistemic. However, the divergence between Joachim's approach and the meso or naNNo approach lies in the individual character of the objects rather than in its size. We need therefore to have a closer look at this factor.

5. Individuation of Nano-objects

It is often said that nanotechnology is dominated by the 'machine metaphor' (Bensaude-Vincent 2004). However, not all nano-objects are machines. Joachim indeed claims to design nanomachines: the molecular wheelbarrow, the rack-and-pinion at the molecular scale, the molecular lander, and the molecular motor are parts of his group's achievements. Beyond the metaphor, however, the theme of the machine is linked to the theme of individuality. Individuality is more important than usefulness to define an object as a machine. Its usefulness to a given application would only allow to specify a system according to the control one has over it at the level of its nanoscale components, but not to *individuate* it.

To explain this, I refer to Gilbert Simondon's philosophy of technology. According to Simondon, technology is the study and the achievement of the technical objects' individuality. This individuality is neither that of technical objects comprehended one by one, because the identity would change along with the successive improvements or inventions. Nor is it the whole consisting of a type or a species, because that individuality would be the projection of a practical use on the object, which describes the operation of man at work rather than the operation of the object. For instance there is a stronger analogy, he says, between the elastic engine and a bow than between the same engine and a steam engine – although from the point of view of *use* the latter two belong to the 'engine' category. A technological object cannot be defined according to its use or fashion, but according to a kind of individuation process that provides consistency to its working principles. Simondon calls this a 'process of concretization' (Simondon 1989b, chapter I, summed up in Simondon 1994, p. 265). In this process, the object shifts from an 'abstract' mode of existence to a more – but never fully – 'concrete' one. The abstract mode is like an applied theory or requirements in which one function analytically corresponds to each component, the object being only the sum of its unitary operations, with no real individuality. In the concrete mode of existence, the object integrates in its working principles the effects of its operation on the external environment. The process of concretization turns the adverse effects and external constraints into operating conditions. This integration of the environment into the working principles turns the object into a technical individual.

STM researchers from Orsay's laboratory of molecular photophysics constantly highlight this feature. According to them, not only "the environment can affect the functioning of a molecular machine" (Riedel *et al.* 2008), but "the surface is a function of the machine".

The 'concrete' machine designer, Simondon explains, thus reasons in terms of an 'associated milieu'. He does not first try to improve the machine's efficiency and then introduce it into its functional environment. Instead, by imagining the machine in its environment, he anticipates the effects of its operation and tries to integrate them into the machine's working principles. That is why the 'associated milieu' is simultaneously chemico-physical and *mental*: it is the milieu associated with the conception of technical principles. The machine designer becomes the object's 'associated milieu', he welcomes the technical principles within him, establishing a link between thought (determined structures and forms) and life (background of thought or mental environment associated with forms) similar to the link between a structured technical object and a natural environment. (Simondon 1989b, p. 60).

Of course, nanomachines are still far from being 'concrete' in Simondon's sense. But they deepen their relation to a chemico-physical 'associated milieu' – atomic surface patterns, energetic conditions, vacuum, and low temperatures allowing stabilizing the object in the STM room. In addition, they integrate a mental environment of a *partnership between the object and the researcher*, often leading the researcher to 'identify' with the object or to mime its working according to a participative relationship: by designing new devices researchers are also designing themselves individually and collectively.

We are therefore dealing with technology in the sense that the working principles of technical objects are carried out and studied. These principles are stable compromises (*mixtes* in French) between *operations* acting according to the natural laws (Simondon 1989b, p. 35) and *intentions* relative to problems that have to be solved. The design of working principles is neither the vertical application of a human law, nor a process occurring without us, but the search for stable compromises between operations and intentions, concrete and abstract, natural and artificial.

The individualization of the object through its functionalization at the nanoscale makes it a machine. That is why today some chemists question the validity of the concept of 'supramolecular chemistry', coined by French chemist Jean-Marie Lehn (1987 Nobel Prize for chemistry), regarding catenane and rotaxane-based molecular machines.[1] For instance, Kay *et al.* (2007, p. 101) argue that "even though their components are not covalently connected, catenanes and rotaxanes are molecules (not supramolecular complexes) as covalent bonds must be broken to separate the constituent parts". With molecular machines, the molecule/supermolecule distinction tends to be referred less to structural features (e.g., the covalent or non-convalent nature of the bond) and more to functional ones. For example, according to Balzani et al. (2008, p. 9), "functionally, the distinction between what is molecular and what is supramolecular should be based on the degree of intercomponent electronic interactions. […] When the interaction energy between units is small compared to the other relevant energy parameters, a system can be considered as a supramolecular species, regardless of the nature of the bound that links the units". Thus, there are some molecular machines in which the components can be linked by chemical bonds of various nature during the operation that is performed: according to the Lehn's 'classical' definition of supramolecular chemistry, these systems should be described as alternatively molecular and supramolecular! But if this distinction is reinterpreted in terms of functions, molecular machine chemists can refer to one and the same large molecule.

In short, the coherence of the functions individualizes the molecule. But what means 'function'? Still following Simondon's conceptions, we argue that in the case of molecular machines, 'function' should not be confounded with 'use'.

It should be recalled that 'function' has first a specific chemical meaning. It refers to a possibility of bonding which gives a selective reactivity to a molecule. For example, when a chemist says he is working at functionalizing a molecule to attach it to a surface, he means that he has to choose the right reactants according to the chemical affinities between species. But supramolecular chemistry expanded the notion of 'function' from chemical function to mechanical and electronic function of a molecule (Schummer

2006). For example, between two rings of a catenane, there is a no chemical function, but a mechanical function.

'Function' thus acquires a technological meaning (still interacting with its chemical meaning) to be interpreted in terms of an operational scheme. For example, Joachim's team has synthesized a molecular wheelbarrow that has been adsorbed and manipulated on a copper surface with the STM's tip (Rapenne et al. 2006). What makes this molecule a wheelbarrow, is its function and not its work or use: C140 H120 is not a wheelbarrow because it could carry a charge (it cannot, at least for the moment). Moreover, supposing that it could carry a charge, for the moment, there is no other way to move in a controlled manner an individual molecule without the enormous STM, the low temperatures stabilizing the molecular object, and so one. One should also notice that there is no need to equip a molecule with wheels to move it on a surface! C140H120 is a wheelbarrow because it instantiates the simplest scheme to transform a translational motion into a rotary motion – a scheme that, in our world, is the one instantiated by a wheelbarrow. The function of a molecular machine is the intrinsic coherence of its operational scheme, regardless of usefulness and performance. The function of a molecular machine is not a means-end relationship, but a relationship between the technical individual and its associated milieu, including the instrumental apparatus. In the case of the wheelbarrow, the operational scheme can only be performed thanks to molecule-surface interactions, molecule-STM's tip interactions, low temperatures, and ultra-high vacuum.

Finally, 'function' has another meaning in that it refers to analogies of operations between different scales. Thus, what researchers are projecting in the nanoscale is not the shape or the usefulness of macroscopic objects, but their operations. 'Function' acts as an analogical operator between the scales. Accordingly, the molecular machine has to be schematized both with the help of intuitions developed in macroscopic scale and according to the specificities of the nanoscale.

Once again, the idea that molecular machines are technological individuations seems to be relevant here. It is the coherence of the functions in a given environment that individualizes the molecule and makes the environment an associated milieu. With this concept of 'molecular machine', molecules are no longer means-for-an-end or raw material waiting to be shaped by a human (or trans-human) project. Molecules are treated as partners, rather than as mere slaves that should be harnessed without paying attention to their mode of existence.

6. Nan^{n}o

What shall we do with Joachim's definition of nanotechnology? Though it does have an epistemic and technological ground, *i.e.* sticking to single atoms, electrons, and molecules by opposition to 'big naNNo' (mesoscopic phenomena and devices), it is too restrictive and obviously linked to Joachim's own positioning in the field. It also allows him to dismiss ethical responsibility and to consider that it is "very much exaggerated" (Joachim & Plévert, 2008, back cover). As SHS scholars, we do not have to share the actors' convictions and should be aware of their demarcation strategies.

Instead of opposing what is 'truly nano' and what is not in order to define nanotechnology, we propose to *characterize nano by the type of technology it instantiates*. The process of individuation of technical objects by integration of their 'associated milieu' may be more important to characterize nanotechnology than the issues of scale and the quantum *versus* classical features, usually mentioned. The process we describe is not confined to a particular scale. Instead, it allows communicating different scales (pico-, nano-, meso-, micro-, milli-). In STM studies, for instance, the so-called 'isolated' molecule is not alone, because it is related to the macroscopic entities of a crystalline surface and the tip of the instrument. In order to deal with a single molecule, the whole instrumental setup must be taken into account. The single molecule is therefore not necessarily "one molecule and always the same one" as Joachim (2005) puts it. It is individuated by the instrumental device. This does not contradict the hypothesis of molecular individuation, but helps understand how instrumentation and image design are part of the molecular machine's 'associated milieu'.

A similar individuation process can be observed in a lot of other nano sub-fields. Biophysical studies of macromolecular machines, while belonging to 'meso' or 'naNNo' in Joachim's sense, are no longer dealing with the statistical object of classical biochemistry, in which proteins have to be crystallized by billions to become subject to x-ray studies. For instance, David Bensimon and Vincent Croquette from the Laboratoire de Physique Statistique at the Ecole Normale Supérieure (Paris) follow an individual protein (DNA polymerase) in real time during DNA replication, thanks to the device of optical or magnetic tweezers (Maier, Bensimon & Croquette 2000). They trap a magnetic bead attached to DNA between two magnetic fields and they apply and measure a force both with the same tool at the scale of individualized proteins and DNA.

Thus, Joachim's definition with its emphasis on the individuation of molecular nanomachines could presumably be extended to many more research fields, even when the instrumentation is different and the objects are bigger, but not in the sense its author put it ('naNo' *versus* 'naNNo').

As a wink to Joachim, I suggest the term 'nan^{n}o', meaning 'nano to the power of n' with as many n's as you like. 'Nan^{n}o' would refer to a functional individualization process of molecular objects in instrumental devices such as the STM. Nanotechnology understood as 'Nan^{n}o' is not concerned with the specificity of nano or with the delimitation between what is nano or what is not: it takes nano in all its variable configurations as long as it is about molecular objects revisited by 'technology' in the sense we use it.

7. Science or Technology?

If the term 'technology', in the sense given above, adequately characterizes the field of molecular machines, does it cover the whole field of nanoresearch?

Most researchers of the French Centre National pour la Recherche Scientifique (CNRS) we have interviewed were reluctant to call their practice 'technology'. For them, (nano)technology is merely about commercial outcomes and marketable products of research. Being physicists or chemists above all, they would rather use the term 'nanosciences', like most of the researchers who use the nano-label in France. They stress the distinction between nanoscience and nanotechnology in order to maintain the values of their discipline away from the purely utilitarian values they associate with technology.

However, there is a big difference between stating that sciences concerned with the molecular scale may be called nanosciences – nobody would deny that – and stating that nano is a *new* science. In the first statement, nanotechnology is a way for *sciences* (plural) to practice and vaunt the laboratory technology. In this meaning, technology does not nullify the disciplinary partitions. In the second statement, about a new *science* (singular) at the molecular scale, it is not clear what we are dealing with. Joachim claims that his experiments open up a new field of knowledge and a new scientific project because they allow "to revisit the laws of physics as we know them today" (Joachim & Plévert 2008, p. 92). Indeed, he aims at submitting the fundamental principles of quantum physics – which he finds too 'smooth', particularly the superposition principle – to new tests at the level of the single molecule. Without questioning the grandeur of this project, nobody can say it will be successful. But because nanoscientists use *approximated* and *highly hybrid* theories in their models to fit their experiments, it remains for us unclear how they will submit fundamental laws to experimental tests at the level of single molecules. Joachim admits that it is impossible to talk about 'nanoscience' (singular) as long as the basic principles of quantum physics remain valid to explain the behavior of his molecular machines.

> If a new phenomenon happened to appear, and quantum laws couldn't explain it, then a new science would rise: the science at the nanometre scale, or nanoscience. Otherwise, what would be the use of inventing a new word to define the field of technical knowledge opened by nanotechnology? [Joachim & Plévert 2008, p. 92]

For instance, in order to challenge the quantum superposition principle, Joachim needs to study the molecule's function – and malfunction – that could independently perform a logical calculation. To him, we are like in James Watt's era, who by extending to its boundaries the mechanics of the steam engine, preceded and allowed Sadi Carnot's conceptualization of a new science, thermodynamics. Joachim intends to do the same with the machine molecules (Joachim & Plévert, 2008, p. 33). For now, this technology consists in a set of procedures and 'technical knowledge'. According to Joachim, only if he pushes it to its limits, will he have a chance to revise the physical laws – provided that a molecular machine does not work according to the received physical laws. Actually, experimentations with molecular machines have shown much unexpected behavior (a molecule never does what the nanotechnologists planned to make it do), but all these 'surprises' have been explained afterwards by means of modeling and simulation according to known (approximated) physical laws.

Researchers who are reluctant to bear the technological nature of their approach are confusing *technology* and *useful applications of science*. Their position is also political if they refuse to identify their research with developing prototypes of future applications, because that would threaten the identity of their discipline. Thus, they often seek refuge in the ideal of 'science for its own sake'. What makes Simondon so precious is his project of dignifying technology: as the regulator of our relationship to nature, technology is not reducible to its uses and concerns knowledge.

Technology in Simondon's sense rejects neither the distinction between science and technology, nor the distinction between specialized scientific disciplines and specialized fields of engineering. It operates before the distinction between fundamental and applied sciences (or between science and utilitarian technology). That is why Simondon called it 'general science' or a 'technique of all techniques' (Simondon 1989b, p. 218). According to Simondon, the key point is that a mechanism operates according to *all* the laws of nature, whether they are known or not. Any technological project would require the universal scientific knowledge if such a knowledge existed (Simondon 1989b, pp. 35-36). But as is does not, because each discipline focuses on a particular perspective or method to address a phenomena, technology still cannot be reduced to scientific knowledge. A machine operating in a complex environment cannot be fully explained simply by applying a corpus of scientific principles. Even if "today, the real technical activity is to be found in the scientific research field" (Simondon 1989a, p. 263), a machine will still be constructed *before* having been entirely planned according to a set of scientific laws.

Nanotechnology in molecular machines practices is intrinsically of techno-logical nature (in Simondon's sense) because (i) it is the study of working principles inside instrumental devices that make them possible (such as the system surface/molecule/tip of the STM); (ii) there is no hierarchy between theory and practice; and (iii) no concern for pure utility or application. Such research belongs neither to basic research, nor to applied research, nor to a hybrid genre. Technology in its practice means a series of *cognitive, non-theoretical,* and *technical* activities that are not primarily useful. Technology is not a mere tool of science, and science is not a mere tool of technology. The interactions between the technical and the cognitive dimensions take place at another level: they point to the object and its 'associated milieu'. The theoretical ambitions (*e.g.*, testing quantum physics) or the practical ambitions (*e.g.*, the chemist's 'synthetic challenges' of building molecules with a particular mechanism) individuate an object such as a molecular machine, but none of these ambitions exhaust its mode of existence.

8. Conclusion

Nanotechnology is a true *techno-logy* in the sense of knowledge of technical operations. The knowledge developed in its practices cannot be reduced to scientific knowledge. Molecular machines are not simply useful objects, although they might become that in the future. They can certainly generate applications, but they leave open other possibilities of constructing meaning and finality in their eventual uses.

Technology, in this sense, excludes all sociological, psychological, and anthropocentric determination from the study of technical objects (Simondon 1989b, p. 24). On the other hand, "the objects' technicity is above all a strictly human reality, literally cultural. Usefulness and symbolism are partly subsequent phenomena of capture and degradation" (Simondon 1960-61, p. 4).

Should the design of molecular machines be supervised by ethics? If by ethics we mean consequential or deontological views about the potential uses of these devices in the future, ethics would become very speculative. However, designing individual molecules is by no means a neutral activity. Design activity is frequently concerned with tensions between *mastery* (the object as a slave) and *care* (the object as a partner deserving to be listened to); between *hubris* ('challenging nature') and *humility* ('we know that the reverse engineering of a complex protein machine is unfeasible').

Although technology, in my understanding, does not determine technical activities and uses, it is not ethically neutral. Even though future uses are not inscribed in the objects' operation, the objects do not leave us totally free – otherwise the ethical valuation would only concern the right way to *use* objects. Instead, these objects condition the world (Arendt 1958), in the sense that they generate new relations to nature, to oneself, and to others.

Characterizing 'nano' by defining its 'technology' does not lead to a definition of what is or what should be ethics of nanotechnology. Nevertheless, it exhorts ethical reflection upon nano avoiding two major traps: 1) raising ethical questions without consideration for the practices of nanotechnology; 2) deciding which question should be considered as an ethical issue or not on the basis of a purely scientific account of what 'nano' is and is not. In my view, the coordination of ethical and epistemological researches on nanotechnology has to occur in a two-way process: While ethics has to be careful with the present practices, epistemology has to be careful with the values informing technological practices.

Note

[1] According to Lehn (1987), "supramolecular chemistry may be defined as 'chemistry beyond the molecule', bearing on the organized entities of higher complexity that result from the association of two or more chemical species held together by intermolecular forces. (…) One may say that supermolecules are to molecules and the intermolecular bond what molecules are to atoms and the covalent bond". A catenane (from the Latin *catena*, chain) is a mechanically-interlocked molecular architecture consisting of two or more interlocked macrocycles. A rotaxane is a mechanically-interlocked molecular architecture consisting of a dumbbell-shaped molecule which is threaded through a macrocycle.

References

Arendt, H.: 1958, *The Human Condition*, Chicago: University of Chicago Press.

Balzani, V.; Credi, A. & Venturi M.: 2008, *Molecular Devices and Machines: Concepts and Perspectives for the Nanoworld*, 2nd ed., Weinheim: Wiley-VCH.

Bennett, C.H.: 1982, 'The Thermodynamics of Computation – a Review', *International Journal for Theoretical Physics*, **21**, 905-940.

Bennett, C.H.: 2003, 'Notes on Landauer's principle, Reversible Computation and Maxwell's Demon', *Studies in History and Philosophy of Modern Physics*, **34**, 501-510.

Bensaude-Vincent, B.: 2004, 'Two Cultures of Nanotechnology?', *HYLE, International Journal for Philosophy of Chemistry*, **10**, 65-82.

Datta, S.: 1997, *Electronic Transport in Mesoscopic Systems*, Cambridge: Cambridge UP.

Joachim, C.; Gimzewski, J.K. & Aviram, A.: 2000, 'Electronics using hybridmolecular and mono-molecular devices', *Nature*, **408**, 541-548.

Joachim, C.: 2005, 'To Be Nano or Not to Be Nano?', *Nature Materials*, **4**, 107-109.

Joachim, C.: 2006, 'The driving power of the quantum superposition principle for molecule machines', *Journal of Physics: Condensed Matter,* **18**, 1935-1942.

Joachim, C.; Guchet, X. & Loeve, S.: 2007, 'Controverses sur l'histoire des nanotechnologies', séminaire *Enjeux anthropologiques, culturels et philosophiques des nanosciences et nanotechnologies*, Institut de Recherche et d'Innovation, Centre Georges Pompidou, Paris, 25 April 2007. [http://www.iri.centrepompidou.fr/seminaire/fonds-documentaires/?browse=Nanotechnologies%252F23_05_2007]

Joachim, C. & Plévert, L.: 2008, *Nanosciences, La révolution invisible*, Paris: Seuil.

Jones, R.A.L.: 2006, 'Hollow Centre – Nanotechnology is a discipline in the throes of an existential crisis', *Nature*, **440**, 995.

Kjølberg, K. & Wickson, F.: 2007, 'Social and Ethical Interactions with Nano: Mapping the Early Literature', *NanoEthics*, **1**, 89-104.

Landauer, R.: 1961, 'Irreversibility and Heat Generation in the Computing Process', *IBM Journal of Research and Development*, **5**, 183-191.

Lehn, J.-M.: 1987, 'Supramolecular Chemistry - Scope and Perspectives. Molecules, Supermolecules, and Molecular Devices', (Nobel Lecture, 1987), *Angewandte Chemie*, **27**, 89-112.

Leigh, D.A.; Kay E.R. & Zerbetto F.: 2007, 'Synthetic Molecular Motors and Mechanical Machines', *Angewandte Chemie*, **46**, 72-191.

Maier, B.; Bensimon, D. & Croquette, V.: 2000, 'Replication by a single DNA polymerase of a stretched single-stranded DNA, *Proceedings of the National Academy of Sciences of the United States of America*, **97**, 12002-7.

Rapenne, G.; Grill, L.; Zambelli, T.; Stojkovic, S.M.; Ample, F.; Moresco, F.; Joachim, C.: 2006, 'Lauching and Landing Single Molecular Wheelbarrows on a Cu(100) Surface', *Chemical Physics Letters*, **431**, 219-222.

Riedel, D.; Mayne, A.; Dujardin, G.; Bellec, A.; Chiarravalotti, F.; Cranney, M. & Lapastis, M.: 2008, 'Probing the movements of a single molecule', *Plein Sud, Special Recherche*, 2008-2009, 74-79. [www.pleinsud.u-psud.fr/specialR2008/en/08_Probing_the_movements_of_a_single_molecule.pdf]

Schummer, J.: 2006, 'Gestalt Switch in Molecular Image Perception: The Aesthetic Origin of Molecular Nanotechnology in Supramolecular Chemistry', *Foundations of Chemistry*, **8**, 53-72.

Simondon, G.: 1989a [1954], *L'individuation psychique et collective*, Paris: Aubier.

Simondon, G.: 1989b [1958], *Du mode d'existence des objets techniques*, Paris: Aubier.

Simondon, G.: 1994 [1958], 'Prospectus pour *Du mode d'existence des objets techniques*', in: Bibliothèque du Collège international de philosophie, *Gilbert Simondon, Une pensée de l'individuation et de la technique*, Paris: Albin Michel, pp 265-267.

Simondon, G.: 1960-61, 'Psychosociologie de la technicité', *Bulletin de l'École pratique de psychologie et de pédagogie de Lyon*, **2** (1960), 127-140, **3** (1961), 227-238, **4**, (1961), 319-350.

Schmid, G.; Decker, M.; Ernst, H.; Fuchs, H.; Grünwald, W.; Grunwald, A.; Hofmann, H.; Mayor, M.; Rathgeber, W.; Simon, U. & Wyrwa, D.: 2003, 'Small dimensions and materials properties – A definition of nanotechnology', Bad Neuenahr: Europäische Akademie (*Graue Reihe*, no. 35). [www.ea-aw.de/fileadmin/downloads/Graue_Reihe/GR_35_Nanotechnology_112003.pdf]

Van Kampen, N.G.: 2007 [1981], *Stochastic Processes in Physics and Chemistry*, 3rd edn., Amsterdam: Elsevier.

Sacha Loeve:
Department of Philosophy, University of Paris 10, 200 avenue de la république, F-92001 Nanterre, France; loevesacha@yahoo.fr