Towards a Practical Form of Epistemology: The Case of Green Chemistry

Jean-Pierre Llored
CREA/Ecole Polytechnique

This paper explores how chemists are transforming their own current background in order to act upon the world without jeopardizing life. In this respect, I will envisage science as both a system of propositions and a set of engaged practices. The scrutiny of chemical innovations will allow me to query the concepts of *paradigm* and that of *scientific community*. In doing so, I will connect the philosophy of science with the philosophy of technology so as to think about our relation with the world.

Keywords: practices, agency, time, affordances, chemical transformations, partnership

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1. Calling for a complementary philosophical approach to science

Philosophers often investigate the discourses of science as primarily a theory-oriented use of language. In so doing, they develop what Gilbert Hottois calls a logotheoretical approach to science (Hottois 2004). In this respect, a philosophy of science amounts to a philosophy of logic and formal representations. Rudolf Carnap asserted: “Philosophy is to be replaced by the logic of science—that is to say, by the logical analysis of the concepts and sentences of the sciences, for the logic of sciences is nothing other than the logical syntax of the language of science” (Carnap 1997, foreword). Philosophers thus scrutinize scientific formalisms as if they were isolatable from the practices within which they are framed and used. In a nutshell, they consider language and its use in the presentation of theories to be the starting points and the main focus of any philosophical enquiry. What about the way science defines and transforms the world and itself within its own practices? What about its

Corresponding author’s address: Jean-Pierre Llored, Ecole Polytechnique/CREA, 91128 Palaiseau cedex, France. Email: jean-pierre.llored@polytechnique.edu.

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ongoing patterns, to refer to Joseph Rouse's terminology? What about a way of articulating the logical face of science with that of its operative capacity to create new materials and symbols?

Postmodernity has shown that science is technologically embedded within institutions. As a result, the dependence of science upon contigent normative structures—cultural, linguistic, logical and others—has been highlighted as well as both its historicity and its social forms of life. The trouble is that philosophy of technology and philosophy of science remain largely unconnected. *Scientific entities*—theories, processes, chemical bodies, particles, and so on—act upon the world and are able to change it radically. New problems arise and older ones need to be reconfigured because of the increasing capacity of science to change life and material things all the way from the microscale to the macroworld. The way science and technology have become intertwined currently in academic research and industry, but also the new ways of doing science within interdisciplinary projects in material sciences, biotechnologies and nanotechnologies to quote but them, call for a practical epistemological shift.

The case of chemistry is particularly relevant for encouraging such a practical enquiry and for developing a complementary philosophical approach, the starting point of which are chemical practices themselves. Following this perspective, questions about science change. They move from truth justification of *descriptions* to articulation and evolution of multifarious *practices*. Before commenting on the gap between the aims of chemistry and its social representations, and before announcing the rise of a new green and sustainable chemistry, we should make sure we understand existing *ways of doing* chemistry. At the same time, we must query their thresholds of meaning and their status in the economy of knowledge, their entanglement with other sciences pure and applied, and their expectations of future developments. A return by philosophers to studies of laboratory practice is thus of paramount interest. It paves the way for studies of local practices and unveils interactions between science, industry, society, and humanity in general. In turning to these studies, philosophers could raise questions about some of the new faces of chemistry.

I shall first study the case of green chemistry. Green chemists are changing the way chemistry is done so as to reduce and control damage to the environment. These changes of practices could induce the reformulation of the operational, symbolic and normative frameworks within which chemists give sense and direction to their actions. I shall then further explain why a practical epistemology of chemistry must connect science and technology. To conclude, I shall point out how a practical form of epistemology can widen both our understanding of what chemists do within society at particular times and our reflection upon ways of dealing with what we call reality.

2. From propositions to engagement

In a paper entitled "Green chemistry: today (and tomorrow)" dealing with the "key drivers" for major chemical changes, the chemist James Clark highlights the reasons why and how chemists are transforming the way they practice chemistry (Clark 2006). In this respect, he identifies three main drivers for change. The *economic driver* which mainly focuses on the increasing costs of waste disposal or for storing hazardous substances. This driver is also related to energy and petrochemical expenses and the increasing fines for pollution. The *societal driver* is moslty concerned with the increasing demands of emerging nations, local and global problems of demography, the poor public image of chemistry and the negative media reporting especially after chemical disasters. This societal driver also takes into account the declining numbers of students studying chemistry and both the public and political demands for damage control. Clark also scrutinizes what he called the *environmental driver* referring to new legislation forcing the testing of all chemicals and the diminishing supplies of non-sustainable resources. The notion of *producer responsibility* remains essential in his paper.

Clark describes the different steps of a chemical production to show how chemists now take account of the environmental impact from the very beginning of a chemical design. For example, he explains how green chemical innovations are integrated into the "pre-manufacturing step" including the biosynthesis of lactic acids, new chemical coumpounds such as "polyactic acid" derived from renewable resources, and so on. He then refers to the "manufacturing step" with its specific green industrial processes to produce ibuprofen or cyclohexanone and also points out the use of supercritical carbon dioxide for hydrogenation. In brief, he emphasizes how chemical processes, reactions and products are *co-evolving* while instrumentation is endlessly adapted to reduce or to detect pollution. Furthermore, he explains how crucial assessments are at this stage of the production chain. Chemists contrive "the green chemistry *metrics*" as tools to measure efficiency in a chemical process. Having made a green chemistry improvement to a chemical process, it is important to be able to quantify the change. In this respect, chemists design new concepts and methods to make assessments reliable, useful and robust. For example, Clark quotes the GlaxoSmithKline[1] formula to assess carbon efficiency, that is to say the ratio between the amount of carbon in a product and the total carbon present in the relevant reactants.

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[1] The English group GlaxoSmithKline is a leader in the pharmaceutical industry. Its slogan is: "Do more, feel better, live longer".

Chemists agree that this metric is a "good simplification" for use in the pharmaceutical industry as it takes into account the stoichiometry of reactants and products. In short, Clark highlights the strong interconnection between chemical methodologies, know-how, and knowledge. Even if his standpoint is mainly technoscientific, he reminds us not to overlook social and industrial contexts and expectations. Clark then evokes the product delivery, the product use for human life or for further chemical or industrial processes and innovations. He finishes his demonstration using the concept of the "end of life" of a chemical body insisting on the "biodegradability requirement".

To sum up, Clark describes the reasons that make chemists advance the recasting of their own activities from within current laboratories and factories. Chemistry is thus understood as deeply embedded in a society and interrelated to it. Moreover, this society defines the meaning of the word 'environment' and the laws and norms that limit our action upon it. Following this line of reasoning, he does not describe chemistry as an autonomous science oriented only by paradigms nor does he consider it to be merely propositional. On the contrary, he depicts it as an *engaged* science that comes to grips not only with social and political requirements but also with the needed co-evolution between industry and academic research.

3. Querying science autonomy

Green chemistry is currently in process. It may succeed in reshaping and transforming chemistry or, maybe, it could fail. However uncertain its future may be, the example of green chemistry is interesting for the philosophers or sociologists of science who investigate scientific changes or "revolutions" or social movements. It seems to escape the internalist/externalist dichotomy and also from other current philosophical oppositions, such as the divergent realist and the constructivist accounts of science. It even escapes most sociological models describing scientific and social movements (Woodhouse and Breyman 2005).

As a matter of fact, chemists synthesise their own objects to satisfy human purposes, and those new chemical bodies act upon the world, transform ecosystems, human societies, and human life in general. Molecules and materials make instrumentations, tools, practices and both human and non-human processes change. Chemists are unable to predict every possible consequence because they do not know how those chemical *actors* interact with other chemical bodies, the world, or ourselves so as to cause new phenomena to emerge. Our interactions with the world partly escape us and go far beyond our range of intelligibility. Chemists thus have to face open-ended interactions that intertwine with what is alleged to be *inside* and *out-*

side science. Innovations encourage new processes that make new innovations and hence new scientific knowledge emerge. New instrumentations can detect lower and lower quantities of chemical bodies paving the way for new environmental norms, while up-to-minute norms foster research for new instrumentations in order to reach lower thresholds of pollutants. Social trends can influence the chemists' choices in cosmetics, pharmaceutical, and food industries, while new chemical products can reshape new social fashions. In this respect, chemical actors can also be called chemical *actants* that intertwine heterogeneous networks, including chemical bodies, our own bodies, the environment, our social institutions, and so on. *Actants* in a network take the shape that they do by virtue of their relations with one another (Latour 1987).

Open-ended processes that entangle diverse ways of thinking and doing chemistry are *actively engaged* not only with the world but also with other sciences and the rest of society. The philosophical dichotomy between science as "objective" and science as a "social construct" is of no relevance in this case. Following Isabelle Stengers, science is a process rather than a product; it is creative, rather than foundational; it creates truths, rather than "The Truth". Its action introduces novelty into the world; it "makes a difference" (Stengers 2000). This difference implies new intelligibility, new questions, but also new agency inside and outside the laboratory to face new challenges whatever their nature may be. As Andrew Pickering asserts: "The standard answer in philosophy and sociology of science was that to understand closure it was necessary to invoke something fixed and unchanging to cut down the space of openness" (Pickering 2001, 504). Pickering develops his idea using the following example:

> [T]he vectors along which Hamilton eventually travelled were singled out not by anything preexisting his practice, but in terms of the specific resistances that emerged in the real-time of his practice and of the specific accommodations that Hamilton made to them [...] that I call the mangle of practice. (Pickering 2001, 505)

The notion of "autonomous community paradigms" and that of "what is inside or outside" a given science are utterly interdependent. Pickering adds:

> In the *Structure* [...] the idea that each scientific community has one big paradigm serves to conjure up a boundary around science—it makes it possible to think about science as a self-sufficient and self-contained entity. (Pickering 2001, 506)

In our case study, green chemistry is not a homogeneous community but encompasses multifarious ways of doing chemistry and chemical communities from nanochemistry to chemical engineering. Green chemistry is not a delineated field. It does not have a pure and unique reference. A chemist who optimizes an extraction process using a supercritical fluid does not make use of the same practice of chemistry as a specialist of molecular assembly using transition metals. They are both chemists and mostly use the same molecular representations, but they do not have the same chemical culture and know-how. Moreover, they do not use the same resources in the same sites with the same aims: their scientific "forms of life" differ. It is the *conjunction* of those forms of life that is subsumed under the label "green chemistry". As Pickering asserts :"[J]ust where the boundary lies between the inside and the outside of any given science becomes a matter for historical enquiry rather than a priori philosophical resolution" (Pickering 2001, 506). So, what do local enquiries about green chemical practices reveal?

4. Beyond reference: Family resemblance and the circulation of concepts

To comply with Pickering's requirement, we choose to follow Denis Diderot's philosophical line investigating what chemists do and what is in action when chemical know-how and knowledge move from one place to another. Diderot aimed at characterizing chemical, technical and scientific practices by considering their specific sites and goals (Diderot 1754). He guided us towards an image of chemistry constantly adopting new techniques and pushing at the frontiers of neighbouring fields of sciences. So, what do local enquiries about green chemical practices reveal?

Fist of all, diverse labels such as "green chemistry", "sustainable chemistry", "ecological chemistry", "chemistry for sustainable development", and so on coexist. What are the differences between these terms?

The debate is open between chemists and other members of society. Let us nevertheless just quote Isabelle Rico-Lattes, a French chemist in charge of French and European programs related to the new chemistry:

> First of all, "green chemistry" does not only refer to the "chemistry of renewable feedstock", even if this is frequently how it is perceived, but refers to the 12 principles developed by Paul Anastas. For me, "chemistry for sustainable development" or "sustainable chemistry" means something else. It is a broader term than green chemistry that integrates the concerns for the economic viability of the result of the research. (Rico-Lattes and Maxim forthcoming)

As the matter of fact, Anastas's principles revolve around (1) the prevention of waste and accident, (2) the optimization of the incorporation of the materials into the final product, (3) the reduction of hazardous chemical synthesis and of the number of compounds in general, (4) the design and use of safer chemicals and processes, (5) energy optimization, (5) the use of renewable feedstocks and catalytic process, (6) the design of biodegradable products, (7) the design of new analytical methods to quantify and control pollution (Anastas and Warner 1998, 30). Those principles are the backbone of green chemistry education. Anastas himself considers them to be a guide for action, the cornerstone of any future chemical invention. A lot of chemists have now begun to qualify his approach calling for a larger description that goes beyond the one and only technoscientific sphere in order to take economic, social and political considerations into account. The necessity of a pluralistic and multicultural approach to the new chemistry is even advocated by sociologists such as Woodhouse and Breyman (2005) in order to (1) secure the financial independence of chemistry from industry, (2) encourage a constructive dialogue between social movements and green chemistry, and (3) to avoid any problem of leadership.

The density of this debate, as well as the diversity of the existing names, is not surprising. As a matter of fact, they just highlight the fact that heterogeneous practices and multifarious fields of research are simultaneously subsumed under a single label. Furthermore, those activities are in process. A local label temporarily emerges from local networks, available resources, interests and projects, leading personalities, local know-how and culture, scientific and ethical values and their interactions and reconfigurations (Llored 2011). The green label is becoming more and more important. It is even the dominant label used today (Linhorst 2010). But it does not preclude the existence of other denominations. The political background should also be considered. The color *green* has indeed a political meaning in France that prevents it from conforming to the alleged neutrality that most scientists favored. Roberts (2005) describes Anastas's principles as a "discursive strategy" to delineate a sharp frontier around green chemistry. Roberts brings to the fore that, in so doing, Anastas constructs a collective identity. Following his line of reasoning, Anastas's a posteriori narration of the history of green chemistry is a current practice used in scientific research in order to (1) gain legitimacy, (2) widen the size of networks, (3) find more funding, and (4) develop infrastructures. This "narrative reconstruction" has a strong heuristic power that enables Anastas to find allies, to connect networks, to create journals and institutions, and to pave the way for international "green symposia" or students training programs.

The careful study of the way scientists consider and refer to the history of their own field is of primary importance for querying both the identity of that field and the way concepts are clarified (Nye 1993). In this respect, both historians and philosophers of chemistry should investigate how a scientific framework is shaped and evolves depending on sites, goals, and community dependence feelings. Following this methodological line, we can assert that Anastas's narrative reshaping of the history of green chemistry is a way to arouse people's feeling of belonging to a larger community, while refining the basic concepts that structure their activities. It is also a strategy for strenghtening Anastas's own legitimacy as a charismatic leader, independently of what his own goals may be. Controversies about denomination—'sustainable chemistry' versus 'green chemistry' and others—are very effective and practical ways of assembling people around concept questions and of refining new definitions, uses, and orientations.

Assigning new meanings, new roles within hierarchies, and new relevant goals and methods to the different protagonists and institutions involved in the process, is a "political" task. There is nothing transcendent in this story, no real primary "frontier" between the inside and the outside of green chemistry, but only an "immanent process of deterritorializations and reterritorializations", to use Deleuze and Guattari's terminology (1987). In line with Pickering's call for local enquiries, Stengers asserts that a scrutiny of a scientific "event" is basic for grasping scientific novelty and evolution without reifying them by means of simple reductions and deductions, and without accepting ready-made philosophical dichotomies. We have to "follow the process" in so far as the process is precisely what is at stake and what is at issue (Stengers 2000). This openness of practices should be integrated into philosophical and epistemological studies of scientific processes. Joseph Rouse asserts:

> As a result, practices are radically open: whether a subsequent action counts as a continuation, transformation, deviation, or opposition to a practice is never fixed by its past instances. These instances are, of course, relevant to the identification and continuation of a practice, but they cannot be decisive in settling whether new cases exemplify the practice; the new cases themselves may, after all, constitute a reinterpretation of their predecessors. Social constructivists' interpretations of practices fail to take adequate account of the openness of the social dimensions of practices. When they insist that social relations or interests are explanatory, they foreclose the possibility that those relations or interests, or even their characterization as social, may be what is at issue in the continuation of the practice. (Rouse 1996, 141)

In his *Brown Book*, Wittgenstein (1969) shows that there is no sharp boundary around a generic term. Its unity is thus the result not of a strict identity or of a unique reference but, on the contrary, of a network of overlapping resemblances none of which run through the totality. Similarities mean subtle "differences" and not identity, foundation or reference. We are dealing with differences *in kind*; a family resemblance is not an open door to an infinite conjunction under the same denomination. Grouping incompatible rules of grammar and empirical propositions under the same label leads to a category mistake (Wittgenstein 1997b,a). Sustainable chemistry, green chemistry, and others, all refer to their own background with their own practices, goals, representations, know-how, and resources. Family resemblance makes the coexistence of different meanings and their interaction possible depending on the *contexts* of use and what chemists aim at doing (Llored 2011). That is the reason why an epistemology of chemistry which scrutinizes chemical practices may enable epistemologists and philosophers to widen their understanding concerning the different interferences, transfers, and translations from one field of research to another while taking distance from hasty generalizations and deductions. This practical epistemology of chemistry encourages closer attention to historical investigations rather than a search for first principles. Following Wittgenstein's *Philosophical Investigations*, we should sharpen our investigations concerning all those language games, uses, and aims.

Stengers suggested distinguishing between two modes of propagation of concepts. The first is achieved through diffusion. In this case the disciplinary origin of the concept is recognized, and we are in the context of an openly metaphorical use. The second case evolves as an epidemic. The source of the concept is forgotten and it is presented as "pure", as cut off from the natural language, and as defined by the formalism of the science that it helps to organize (Stengers 1987). In a complementary though different perspective, Deleuze and Guattari gave an account of a composite knowledge formation by putting forward the thesis of mobility inherent in the concept that joins together the pieces or the components that come from other concepts, which answered other problems and supposed other co-creations. According to them, a concept does not require only one problem under which it alters or replaces preceding concepts, but, rather, a crossroads of problems where it is combined with other coexistent concepts (Deleuze and Guattari 1991, 23–24).

The concepts that circulate between heterogeneous fields of green chemistry need to be further studied by means of a practical epistemology. We have "to follow" each "difference" considering chemists' projects and what is at stake within each field that "shares" this family resemblance. Some concepts come from other realms such as sustainable development, ecology, and ecodesign. They are then translated into the green chemical schemes of a given domain. Others come from green chemical practices themselves such as atom economy and ecochemistry. A practical epistemology of chemistry could take the following questions as starting points to its study of practices: (1) how does the concept of sustainable development circulate from ecology to chemistry while encountering economy, politics and biology? (2) What are its role and its status in chemistry? (3) Is it possible for current green chemistry to transform such a concept? (4) What are the current relations between those concepts? We need a wide range of local studies to understand the interactions between diverse fields of practice and research, the modes of propagation or of translation involved, and the creativity within "green chemistry" (Llored forthcoming).

5. Beyond Kuhn's paradigms and revolutions?

Let us now illustrate the diversity of those evolving forms of life using the example of the French interdisciplinary program "Chemistry for Sustainable Development"—CPDD in French—developed and supported by the National Center for Scientific Research (CNRS) since 2006. CPDD aims at initiating small-scale interdisciplinary collaborations, with potential to grow into wider projects. In their common work *Sustainable Chemistry*, Rico-Lattes, who first supervised the CPDD program, and Laura Maxim, a French researcher in social sciences, draw attention to the contribution of different disciplines to sustainable chemistry (Rico-Lattes and Maxim forthcoming). They explain that the CPDD program has been structured into four "networks"—each of which includes several working teams—that correspond to four major goals for interdisciplinarity in sustainable chemistry:

(1) The use of renewable resources as basic materials to synthesize new molecules and materials. This first network mostly involves biology, agronomy, and renewable feedstock chemistry.

(2) The implementation of the principles of green chemistry in new schemes of synthesis including biotechnologies. This network entangles different fields of chemistry such as catalysis, multi-stage organic and inorganic syntheses that were not necessarily connected so far.

(3) The optimization of sustainable processes of chemical synthesis engaging both chemistry and chemical engineering.

(4) The evaluation and the reduction of the impact of chemistry on the environment that bring together ecology, life sciences, analytical chemistry, physics and toxicology. For example, the aforementioned metrics are currently used in this context.

Those fields previously existed within separate projects, but they are now involved in a common program with precise goals and evaluation timing. This situation is an "event"; it creates "a difference" to use Stenger's vocabulary (Stengers 2000). This situation "requires change and innovation in all aspects of research (structure, function, vocabulary, and evaluation patterns)" (Rico-Lattes and Maxim forthcoming). In a nutshell, this "difference" fosters the co-evolution of multifarious practices and the emergence of new ways of working.

Rico-Lattes and Maxim clearly explain that those four networks face the interdisciplinary requirement differently depending on their specific situation in French society. In this respect, they show that some researchers belonging to the first network were already involved in projects on sustainable chemistry before the CPDD, especially those who work on renewable feedstock such as biomass. Those researchers—industrial and scholarly—are used to collaborating with life sciences experts from the National Institute for Research in Agronomy—INRA in French—to study biological mechanisms and interactions. Connections and structures thus already pre-existed and people have already developed ways of working together. This is undoubtedly not the case for researchers coming from the second and the third networks focused on chemistry and on processes respectively. They previously belonged to different institutions mainly deprived of cross-boundary actions. As to the fourth network, Rico-Lattes and Maxim (forthcoming) point out that: "the interface between chemistry and toxicology and ecotoxicology is more difficult to establish than for other disciplines, simply because France is extremely short of toxicologists and ecotoxicologists." The situation is likely to change because of the implementation of the European regulation REACH—Registration, Evaluation, Authorization and Restriction of Chemicals—in force since 2007. This regulation requires very precise and rigorous data on the chemical properties, the toxicological effects, and the environmental impact of all molecules before they can be added to or retained on the market. France is nonetheless unable to meet this demand, because of the scarcity of (eco)toxicology researchers and of the lack of relevant teaching programs in universities. Interactions are in process, the French story is going ahead. In brief, in some cases, interdisciplinarity changed and is still changing prior practices. According to Rico-Lattes and Maxim, the crucial exchanges arose at the interface between chemical engineering and synthetic chemistry, and between chemistry and environmental sciences. They illustrate their statement with two insightful examples: (1) the first is about the interface between chemical engineering and synthetic chemistry that deals with process intensification and implementation of synthetic micro-reactors; (2) the second deals with the interface between chemistry and environmental sciences, that is the association between chemistry and biotechnologies. They then query the practical conditions required to produce interdisciplinary work. In this respect, they insist on the availability of financial and institutional support, the ability to overcome communication problems between the teams involved, and the possibilities for promoting results, both in the researchers' career and in industrial applications (Rico-Lattes and Maxim forthcoming). Their enquiry is noticeably specific to France: Other studies need to be developed concerning other countries.

This amazing work led by Rico-Lattes and Maxim clearly illustrates the crossroads of problems that were evoked by Deleuze and Guattari while grasping relations and co-creations between concepts. This study also helps us to shed light on what a family resemblance is. As a matter of fact, the dynamic overlaps of diverse networks generate new similarities and make it possible for a large collection of words and practices to co-exist and to co-evolve within various collectivities, be they scientific or not. Finally, it also emphasizes the importance of ongoing interfaces in the active process.

Supporting Clark's conclusion, let us point out that changing both processes and ways of doing chemistry requires huge financial supports and interconnections. It is thus basically impossible for green chemistry to be an independent realm of chemistry. Its birth and growth come from current chemical institutions. Green chemistry is thus the result of a gradual "shift" from existing multifarious chemical fields. In this respect, the current laboratories which are now labelled "green" need to develop other chemical activities to "survive". They have to adapt and multiply their own purposes and strategies in order to find funding. They develop green activities in parallel with other more classical chemical transformations. To conclude, networks of "differences" that underpin green chemistry resemblances are basically co-evolving within standard chemical networks. Crossroads are essential, constitutive, and multifarious. Frontiers between the inside and the outside of green chemical activities are anything but sharp. Interfaces between different chemical practices; the industry; and the university; solids, liquids, gases and hybrids; environmental, economic and societal "drivers"; are constitutively active and often dynamically interrelated. As Rouse asserts: "Practices are spatiotemporally open, that is, they do not demarcate and cannot be confined within spatially or temporally *bounded* regions of the world" (Rouse 1996, 135). Our current chemical action over the world is not fixed by its past instances. Furthermore, the "world" indefinitely widens the space of laboratory activities because of damages that span all aspects of humankind in relation to nature. The surrounding world is now the *global* world. From within the current institutional settings of laboratories and factories, chemists now: (1) take into account the life cycle of a chemical compound from the outset (design, manufacture, use and degradation); (2) tailor chemistry considering the consequences of its activities over the world—in this respect our world is becoming a partner—; (3) entangle time, society, agency (human or non-human) and the world. Those changes can be considered as three major upheavals in current chemistry (Llored 2011). The world, as well as molecules and materials, are by no means *passive objects* that scientists merely have to investigate. On the contrary, they are partners which go far beyond our expectations and deductions, partners which act upon and transform our theories, instrumentations, ecosystems and societies. Networks, crossroads, and interfaces are ongoing patterns that make chemical changes hang and hold together. As a result, chemistry is gradually transforming its own frameworks from within—and in parallel with—its everyday practices while those changes similarly spark off a spate of new networks, crossroads and interfaces. Philosophers often refer to a *dynamic of intersubjectivity* in order to account for achievements within a particular field of research and to explain the possibility of the research itself. It is an *a posteriori* understanding of the current state of affairs. Let us simply point out that this dynamic is nevertheless not always "prior". This is so in particular when what is at stake is the definition of the conditions under which a particular group of scientists can hold together with other heterogeneous communities (Stengers 2000, 174–177). In this context, chemists are not engaged in an intersubjectivity dynamic. They have indeed to invent new links and to continually negotiate their connections in order to make the group evolution intelligible and satisfactory both for its members and for other related groups. There is a difference in kind between an *intersubjectivity in action* and a pre-existing dynamical one.

Philosophers should carefully scrutinize those open-ended circumstances because these call Kuhn's paradigm model and revolutions into question. Relations and crossroads jeopardize the underpinning "field autonomy" assumed by Kuhn. They raise other interesting questions concerning: (1) the interdisciplinary impact on such scientific changes and innovations, (2) the relevance of the separation of technique from science when envisaging those changes and "revolutions", and (3) the meaning of the word "practice" in Kuhn's approach to scientific revolutions. The enquiry is open, so that I believe that a practical form of epistemology of chemistry should play a significant role in this kind of philosophical debate. But a "closer attention" to current chemical changes is required before drawing any hasty conclusions. Let us point out how changes are occuring that is to say, let us answer the question: What are green chemists doing exactly?

6. Reconfiguring chemistry: co-evolution and entanglements

Scientists from the different networks described by Rico-Lattes and Maxim contrive new tools to assess and to understand the full range of the impact of their actions on the world. In doing so, they integrate societal, economic, and political demands. They should not consider the full range of their actions merely in terms of physical effects. As Joseph C. Pitt asserts: "What these changes signify is to be understood against our values and our goals" (Pitt 2011, 25). The crossroads between green chemistry, other sciences, and society force chemists to constantly reevaluate the assumptions, goals, values, practices, and background knowledge that they use to make the decision that led to the action that had those consequences. Following Charles S. Peirce's vocabulary—while widening it to chemical practices and outside semantics boundaries—chemists gradually "clarify" their concepts (Peirce 1955a). Ethical concerns are percolating through chemical grounds. A careful philosophical study is needed to follow this relation between chemistry and ethics Llored (forthcoming). Chemists are thus "pragmatists" to the extent that they collectively improve their instrumentation, their syntheses, and the meanings of their concepts and scientific vocabulary by considering their long run consequences. Peirce pointed out

> Suffice it is to say once more that pragmatism is, in itself, no doctrine of metaphysics, no attempt to determine any truth of things. It is merely a method of ascertaining the meanings of hard words and of abstract concepts . . . All pragmatists will further agree that their method of ascertaining the meaning of words and concepts is no other than that experimental method by which all the successful sciences (in which number nobody in his senses would include metaphysics) have reached the degrees of certainty that are severally proper to them today; this experimental method being itself nothing but a particular application of the older logical rule, "By their fruits ye shall know them." (Peirce 1955b, 270)

Let us illustrate this point choosing a variety of examples.

The atom economy concept (Trost 1991) was quickly integrated into the twelve Principles by Anastas in order to maximize the incorporation of all materials used in the process into the final product. This key concept plays an important role in the reshaping of the design of compounds thus paving the way for new synthetic schemes, processes, and skills. Pickering asserts:

> My basic image of science is a performative one, in which the performances—the doings—of human and material agency come to the fore. Scientists are human agents in a field of material agency which they struggle to capture in machines. Further, human and material agency, are reciprocally and emergently intertwined in this struggle. Their contours emerge in the temporality of practice and are definitional of and sustain one another. Existing culture constitutes the surface of emergence for the intentional structure of scientific practice, and such practices consist in the reciprocal tuning of human and material, tuning that can itself reconfigure human intentions. The upshot is, on occasion, the reconfiguration and extension of scientific culture. (Pickering 1995, 21)

Following Anastas's principles while retroactively broadening their contents thanks to their new practices, chemists change the operative chemical framework by contriving, for example, (1) solar-chemical machines to synthetise new molecules such as Juglone with medium concentrated sunlight (Oelgemöller et al. 2006), (2) a miniaturized apparatus to achieve multiple reactions and separations (Hemantkumar et al. 2007), (3) new continuous flow processes to achieve a highly selective chemical synthesis that some chemists regard as a "new paradigm for molecular assembly" (Baxendale et al. 2006), and (4) new ways of exploring and using chemical interfaces to change chemical properties of solid alloys (Rabu et al. 1999). These new devices and instruments gain new intelligibility within the global activity in process. Following Rouse's line of reasoning:

> Practices are not just patterns of action, but the meaningful configurations of the world within which actions can take place intelligibly, and thus practices incorporate the objects that they are enacted with and on and the settings in which they are enacted. (Rouse 1996, 135)

The chemistry/world partnership is made intelligible thanks to a set of increasing scientific, ethical, economic, and political perspectives. In this context, the concept of ecodesign is co-arising with the development of green metrics.

Let us simply develop the manner in which chemists adapt and develop new tools to change industrial production from the outset. The processes of design must now respond to a global issue of reduction of environmental impacts at each stage of the manufacturing process. Chemists are thus integrating "ecodesign" into the process. In this respect, life cycle analysis—LCA—is a useful tool for the identification of environmental impacts in so far as it enables chemists to quantify and to compare impacts related both to available resources and to the different ways of producing, delivering, and recycling chemicals. LCA guides chemists' choices and enables them to make decisions regarding further innovations. LCA is fourfold, since it depends upon (1) the definition of the aims and the framework which includes parameters such as the inclusion threshold—the lowest mass to be taken into account, the toxicity, the energy consumption and the functional unit. This quantity allows one to assess the function of the system of examined products and to compare different systems, performing the same function, (2) the *life cycle inventory* that consists of flows of materials (minerals, iron, water…) and energy (oil, gas, coal,…) entering in the system under study and the corresponding outgoing flows (solid waste, emissions gaseous or liquid,…), (3) the evaluation of the impacts of life cycle defining impact categories and various weighting impact indicators to achieve calculations from and against databases, and (4) the interpretation of the calculations that allows the identification of the steps that need improvement in order to reduce environmental damage (Caillol forthcoming).

New methods, concepts, taxonomies, and databases thus appear at the crossroads of various fields. Chemists, biologists, industrialists, and toxicologists are then asked to interpret the impact results. In doing so, they must allow various kinds of expertise to co-exist. Achieving such a challenge practically is anything but simple. Caillol asserts:

> However we have previously seen that the solution of a problem may lie outside the selected elements, as the ecodesigned solution. Therefore, this LCA tool has to evolve to make it more usable in a process of innovation. But the more restrictive limitations of this tool are methodological and qualitative. They are qualitative because the relevance of the data is fundamental in the assessment of impacts and these data are not always relevant or updated in the databases, they are not always representative of local reality. They are methodological because this tool allows a comparison in a defined time, evaluates relative impacts, and does not take into account the margin of progress of the technologies that it compares. Moreover, the definition of the hypotheses, the borders, the functional unit, followed by allocations rules or the proposed end of life, can significantly alter the results. Thus, this life cycle analysis tool should evolve to address these limitations and to better assess certain impacts related to toxicity and nuisances. (Caillol forthcoming)

Chemists and their various related colleagues thus enter into an open-ended process of trials and errors to make their work more accurate. Caillol adds:

> [W]e need new tools giving directions to guide the selection of researchers and chemists. It becomes more important to assist the process of innovation with a piloting tool, "*gate to gate*", rather than the conclusion of a comprehensive *a posteriori* analysis. And it is important to extend this environmental design to all the projects of the chemical industry to give reality to ecodesign in the industry. (Caillol forthcoming)

Following this line of reasoning, he advocates the extension and the update of the collections of inventory data while connecting them to the classification of dangerous substances.

An epistemology of chemistry that also takes account of current practices can thus be helpful to understand what is at issue at such methodological and normative crossroads. It can also help chemists to understand their work better. As a matter of fact, epistemologists could investigate the construction of those impact factors and query chemists' modeling. They could help chemists to make some choices especially when the data do not exist, are not reliable, and may not be able to be retrieved. What should chemists decide in such a situation? Should they achieve an LCA? Should they adopt other criteria? Epistemological, philosophical, and historical insights should be of interest concerning methods, calibrations, and ethical concerns. Following this cooperative line, I ask Sylvain Caillol and others, such as Isabelle Rico-Lattes and Laura Maxim, to scrutinize their own chemical practices and to ask some methodological, metrological, and epistemological questions within a collective book dealing with philosophy of chemistry (Llored forthcoming). Caillol thus calls for a closer co-operation:

> In this sense, if chemists, engineers, biologists, toxicologists and ecotoxicologists are involved, it seems equally important to involve historians, philosophers, and epistemologists in the interpretation of the results of the LCA in a dynamic of sustainable development of civilization. Indeed, the notions of negative externalities—environmental impacts—must be considered in the light of the progress made in a historical and philosophical perspective. A life-cycle analysis is only an environmental analysis and it must be supplemented by a societal component—through societal life cycle analysis—in which the place of historians, economists, philosophers may be further increased. (Caillol forthcoming)

A shift towards a practical epistemology of chemistry is therefore in process. It offers a complementary approach to perspectives in analytical philosophy while being able to collaborate with scientists actively. It studies both what scientists are representing and how they act upon and transform the world. This kind of epistemology may also help philosophers who study scientific practices to reflect upon the alternative between an approach which conceive practices normatively, on the one hand, and an approach focused on social or natural regularities, on the other. This example also highlights the fact that philosophers of sciences must reassess the frontiers previously delineated between pure and applied sciences, or between industrialists, scientists, engineers, and scholars if they want to understand how green chemistry is developing and what this ongoing field of multifarious practices is telling them about doing science in current society. Carsten Reinhardt and Harm G. Schröter assert: "Chemistry appears to be the ideal case for arguing in favour of a strong interrelationship between academia and industry" (Reinhardt and Schröter 2004). Once again, another classical philosophical taxonomy needs to be investigated from a complementary practical standpoint.

Chemists are changing their linguistic practices from within interdisciplinarity projects as well. As a consequence, the word 'material' is more and more used and sometimes replaces the word 'substance' Bensaude-Vincent (forthcoming). Engineering and architectural designs cross the chemical frontiers so much so that it is quite usual to find terms such as 'molecular machines and architectures' in chemical papers related to nanochemistry, biochemistry, biotechnology, supramolecular chemistry, and environmental chemistry. The case of rotaxane is particularly relevant. This molecule contains a macrocycle and a dumbbell shaped molecule. Its synthesis encourages new devices and conceptual schemes the denominations of which are 'clipping', 'capping', 'slipping', and 'activate templates'. All those words are now circulating into a new linguistic chemical space widened by the design vocabulary. It is now a common state of affairs to connect a cage molecule from a liquid or gas phase to a solid surface matrix in order to trap ions selectively (Barbette et al. 2004). This chemical synthesis is "in between" material science and organic synthesis and uses physical chemistry's analytical resources, such as the fluorescence emision of an ionophor to quantify heavy metal pollutants in a sample. The vocabulary of fluorescence is thus closely related to green chemical phenomena. This is not the end of the story, and further insights can be proposed. Indeed, the materials used in those interfacial devices are constantly improved thanks to engineering research. Both materials engineering and the vocabulary related to it are influencing chemists' own vocabulary and the ways they are recasting their current practices. As Rouse points out: "Practices are always simultaneously material and discursive" (Rouse 1996, 135). A co-stabilization of instruments, processes, and models with linguistic, normative, and discursive chemical devices is in process. Following Roberts' approach, it could be of interest for a practical epistemology of chemistry to investigate how Anastas and others use these linguistic changes to develop narrative devices regarding the manner in which green chemistry is now evolving. Green chemists entangle ways of doing science and transform them within ongoing open-ended processes of research. In doing so, they develop narrative reconstructions from within their practices in order to make new skills and schemes intelligible while enabling them to enact new green goals. Following Rouse's statements: "What results is not a systematic unification of the achievements of different scientific disciplines but a complex and partial overlap and interaction among the ways those disciplines develop over time" (Rouse 1996, 177). Agency and temporality enter into a scene that was previously occupied by truth justification. As a consequence, philosophers have to think about science and technology at the same time.

7. Thinking science and technology equally

Those operative, conceptual, and linguistic changes call into question the current interplay between doing science and engineering. In this respect, "engineering research is just as fundamental as scientific research" (Pitt 2011, 158). Following Diderot's line, developed in his *Pensées sur l'interprétation de la nature* (1754), a philosopher of science who studies green chemistry should thus consider the context, say, the *terrain* in which chemical *labour* is done. He/she should come back to laboratories to investigate the technological infrastructure of science understood as "a historically determined set of mutually supporting artifacts and structures that enable human activity and provide the means for its developments" (Pitt 2000, 129). The kind of epistemology required is not merely normative to the extent that it has to assess scientific results and theories from a justified truth standpoint. It should also be a practical approach of ongoing patterns of action at the same time. In this respect, the kind of broader philosophy required to underpin this new kind of epistemology should articulate science and engineering, normativity and regularities (Rouse 2002), what is operative and what is symbolic (Hottois 1996). We need another background in which philosophy of science and philosophy of technology cease to be cut off from one another. As Pitts asserts: "[T]he philosophical job is on-going, it never ends, because the complexity of the world is as much a function of what human beings do as anything else" (Pitt 2011, 28). He adds:

> When we pay attention to historical contexts we also see that few, if any, philosophical questions are perennial except in the most trivial sense. It is only when we accept the historically contextualized nature of philosophy itself that we can truly understand the emergence of new areas of philosophical concern such as philosophy of technology. (Pitt 2011, 47)

New ways of doing science arise, new problems that engage science have to be formulated and faced. In the same way new philosophical questions thus emerge concerning sciences, society, ethics, aesthetic and power to cite but a few. A practical epistemology of chemistry should pave the way for more local enquiries regarding what is at stake and so what is at issue in current green chemistry laboratories and factories. In this respect, "[a] rotation in the laboratory would have been good for these philosophers" as the Nobel prize winning chemist Roald Hoffmann asserts (Hoffmann 2007). Researchers should scrutinize further current instrumentation and ongoing practices—be they operative, symbolic or conceptual. Following this line of approach, they should further study the way chemists act upon the world and our society, and the retroactive ways by which the world and our society act upon chemistry's configuration and public image. As Pickering asserts:

> [...] the center of gravity lies elsewhere, at the point of intersection of human and material agency. The trajectory of evolution of the social has here to be understood in terms of emergent resistances and accomodations at the interface of these heterogeneous realms. (Pickering 1995, 168)

In this respect, the dichotomies between science and technology, nature and culture, discovery and invention and many others have to be reconfigured and not merely deleted, as it is sometimes argued in postmodern approaches. Those categories are basic for shaping the space of reflection.They are the open-ended conditions of possibilities of any philosophical enquiry and taxonomy. They give us a reflexive account of how our langage works, rather than of what reality is "in itself" (Wittgenstein 1997b). This is not how the story ends, however. As I previously asserted, we do not control all the consequences of our actions upon the world. Chemicals unpredictably transform ecosystems, societies, and ourselves. Green chemistry is an attempt, among others, to consider the world as a partner. This partnership queries what philosophers mean when they think about *reality* and the world.

Following Gilbert Hottois (1996, 2004), who first introduced the term "technosciences", we can conclude that studying sciences philosophically needs: (1) no logotheoretical primacy; (2) no primacy for human interests and social constructions because of the world's resistances and multifarious temporalities. We have to consider *homo loquax* as well as *homo faber*. Philosophers should not reduce practices to their symbolic aspects but also acccount for their operative and performative transformation of the world. Within some contexts, the interplay between technology and science is so strong that it practically becomes impossible to draw a sharp delineating line between them. We have thus to grasp the emergent whole philosophically. Hottois reminds us that technoscience is primarily concerned with the mutation and the possible disappearance of humankind due to our actions over the world. We have thus to recontextualize our human condition within the temporality of the universe, considering our possible extinction. According to Hottois, we must avoid the philosophical mistake of reducing the understanding of technosciences to an anthropological and an antropomorphological standpoint. He thus pleads for a "trans-anthropological" account of technosciences. In this respect, we should consider the radical alterity and openness of the future in the very long run. No one can actually foresee what our actions—chemical and otherwise—are likely to imply in a future that is extremely remote. The power and the possibilities involved in technoscience go beyond the classical understanding of technology as the externalization of latent human capacities and of the teleology and the eschatology related to it (Hottois 1996). Technosciences go beyond our anthropological difference with other species, the symbolic singularity of our forms of life. This anthropological stance is itself shaken by internal and external non-symbolic processes. We have to accept that the naturalization of the anthropological difference is mainly concerned with its operationalization. Theoretical descriptions, symbolizations of all kinds, and reflections can only interact with this operationalization without anticipating it nor being able to replace it (Hottois 1996, 209). The naturalization of our anthropological difference is the result of a natural, physical, causal, and non-necessary operativity, that is to say, it is opened to the intervention of technology. Symbols are not a starting point. The remote future is a challenge for conceptualization. We should not deprive ourselves of considering its own development. The temporality engaged by technosciences cannot be symbolized or historicized from the outset: we cannot put its actualization aside. The time of eschatology and utopias is vanishing. Our *relation* with the world is not basically symbolic but, rather, technical and operative. We take part of the production of the future. We interfere with the process with our resistances and accomodations. We have thus to recognize that the dynamic of anthropological processes is, at least, partly independent from our symbolic activities (Hottois 1996, 214–215). We have thus to contrive a new interplay between philosophy, technology, and sciences. The operative universality of technosciences is likely to interest philosophers in search for universality. Universality has to be understood from an *operative causality*. Technosciences should require the universality of philosophy as the unique appropriate kind of symbolic interrelation (Hottois 1996, 217). Technosciences explore the cosmos, nature, and living systems; they are non- or trans-anthropological, and sometimes considered to be inhuman. A practical epistemology and philosophy of science is needed to articulate symbols and technosciences differently and to face the crucial societal choices and ethical problems of our present time. The epistemological studies of practices should provide philosophers and other actors within society with interesting information that will enable them both to take distance themselves from hasty idealizations and to sharpen the debate. In this respect, green chemistry as well as chemistry should help philosophers to create new bridges between symbols and action, between representing and intervening.

8. Concluding remarks

Rouse claims that:

> Agency and agents (not necessarily limited to individual human beings) who participate in practices are both partially constituted by how that participation actually develops, and in this sense, 'practice' is a more basic category than 'subject' or 'agent'. (Rouse 1996, 135)

In this respect, green chemistry is neither exhaustively logical nor social. Philosophers have thus an "interesting" challenge with which to cope. The word 'interesting' is understood in its etymological sense of 'inter-esse', a possible translation of which is 'that which is in between'. We need another theory of science, in which science is not understood and described merely as a field of knowledge but also as a field of ongoing practices. This is precisely what I aimed at pointing out within this paper when insisting on the social-political approach to science and technology. As Rein Vihalemm asserts: "Knowledge must be regarded as the process of understanding how the world is formed in practice, of how it becomes defined" (Vihalemm forthcoming). According to him, chemistry is relevant for analysing science as a special kind of socio-historical practical activity.

In this respect, Rom Harré's concept of affordance could be of importance for connecting science, technology, philosophy, and what we call *reality*. The apparatus, its nature, and its way of working cannot be detached from physical phenomena. With a different apparatus the experimenter can get the subatomic world to *afford* interference phenomena with the same starting point as the experiment that afforded particles. It is a mistake to read back from products to constituents—atoms do not contain electrons as components, but they are such as to afford electrons to a suitable apparatus and under suitable manipulations (Harré forthcoming). An alembic affords essential oils from raw plants while lasers afford chemical fluorescence. Harré's approach could become a spring for a philosophy that queries science and technology as whole material activities. I have suggested elsewhere that the partnership developed by green chemists with the world may provide new arguments in so far as "technosciences" are now affording new phenomena related to our new form of actions over the world (Llored 2011). More than ever, a debate between science, technology, philosophy, ethics, politics, and humanity in general is open concerning our relation with the world.

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