Foundations of Chemical Aesthetics

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Abstract: In these prolegomena to a chemical aesthetics, eleven separate theses are asserted: (1) the natural is more beautiful; (2) the artificial is more beautiful; (3) the invisible is yet more beautiful than the visible; (4) the need for visualization is unavoidable; the beauty of chemistry stems from (5) an inner logic and (6) its unpredictability; (7) any change is handsome on account of its invariant elements; (8) the beauty in any change is the fleeting instant; the beauty of chemistry is that it is (9) a science of the complex and (10) a science of the simple; (11) a new contemporary art has been born.

Keywords: *artificial, invisible, natural, unexpected, wonder.*

Introduction

Chemistry and painting share a fascination with color. Both see it, not so much as a quality of light – as a component of it, which Newton with the prism established – but perhaps first and misleadingly, as an essence of matter. Chemists and artists play with pigments (insoluble colored solid particles) and with dyes (soluble substances able at transferring their color onto a support, such as paper or linen); the former as manufacturers and the latter as consumers and users.

Sight, smell, and touch are primary sensations to the chemist. Sight is arguably the most important sensory perception, as it is to other scientists. We see a color change in a flask. We see a solid precipitate from a solution. We watch some smoke coming out of a mixture. All these are manifestations of protean nature, of a material sample undergoing a chemical metamorphosis – as reactions were termed for quite a few centuries. [1]

Thus an essential dimension of chemistry is visual perception, of a lovely color or, much more important, of a change in color, in the aspect of a given preparation. Take as an example the discovery of Prussian blue.[2] The blue was a big surprise. In 1710, Herr Diesbach, a manufacturer of dyes in Berlin, was working with cochineal red – *i.e.* with a natural dye, red in color, from the abdomen of females of the Mexican insect *Dactylopius coccus*, which lives on *Opuntia* prickly pear cacti. Diesbach, presumably in order to purify cochineal

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red, resolved to prepare a precipitate. He added potash to the solution he had prepared. He was flabbergasted with his serendipitous observation of the formation of quite another dye, Prussian blue as it came to be named.

Diesbach's merit was his persistence, in the face of an unexpected result. He might have thrown away the contents of the flask, and resumed his usual procedure for precipitation of cochineal red. He did not – to our benefit.

Chemistry thus might be defined from the wondering at change. What kind of wondering? The active kind, keen on elucidation and explanation. What kind of change? Primarily, modifications of the visible aspect of things. The art of the chemist produces such alterations, which are thus un-natural and indeed artificial.

In nature, things have usually a characteristic color. Often, they pass on their name to it: cherries or a piece of hot iron are red, oranges are orange, Burgundy wine is burgundy red, and painters have on their palette cadmium yellow and cobalt blue. Changes of natural colors are relatively few and indeed symptomatic of a chemical process: hydrangea petals becoming blue or pink depending on the soil acidity; many fruits turning from green to red upon maturation; tree leaves undergoing the converse in autumn; and decaying organic matter becoming brownish and slimy. Hence, as Herr Diesbach was quick to notice and later to bank on (he managed to keep his procedure secret for quite a few years), a sudden switch of a material sample from red to blue, or vice versa, and many other such color changes, are very much characteristic signs of the intervention of a chemical process.

I am looking at a waterfall. What is admirable about it? Why do people look at it with a sense of wonder? The phenomenon of water flowing over a cliff combines reproducibility and an intrinsic irregularity. Also, in the process of falling, water has become white. Normally clear and transparent, the familiar fluid has become opaque. It now scatters light instead of letting it go through. Even when we understand rationally the explanation for such an alteration in appearance, we continue to find it both extraordinary and something to wonder at – a thing of beauty.[3]

Likewise, having inherited all the various tinctures from alchemy – such as the tincture of a metal to give it the look of another, nobler metal – chemistry has remained the art of metamorphoses. It does routinely what physics (the rainbow, the waterfall, *etc.*) does exceptionally. Chemistry, in effecting visible material changes, often achieves the artifice of make-believe.

It creates a world of entities, fictional but not fictive, since they do exist. It has inherited the turn of mind that the Greeks of antiquity termed *metis*, at which Daedalus excelled in his designing of machines (*daidala*) and other simulacra.[4] In so doing, chemistry achieves often the beautiful.

Beauty, beyond being an attribute of some natural things – such as a rounded pebble, a sea shell, a bird feather… –[5] can also result from artificial procedures changing the aspect of things: their color, their texture, their smoothness or graininess, their density, their hardness, the sheen, *etc.*

Hence, chemistry extends our dominion over the world. After the child (genetic epistemology) has mastered sensory experiences of the environment, chemistry is the name of the conquest I have just described – that of at first apparent material changes. The paradox, to which we shall return, is that chemistry becomes a science only by positing invisible entities to account for these visible changes. In any case, chemical science assumes a philosophical position, that of realism – of naive realism to start with.

Is the natural or the artificial more beautiful? The question arises, for instance about the molecular structure of a natural product being subjected to its total synthesis. There is no question that, when for instance Robert Burns Woodward wielded the art of synthesis, the aesthetic component was a major determinant. Why then do we not examine these rival theses before proceeding further?

Thesis A. The natural is more beautiful

Thesis A is grounded in metaphysics, in the notion of the inferiority of the man-made as compared to the God-made, to nature. The underlying notion is for the human animal to be a minute part, not such an interesting one at that, in the cosmos. Whether nature as a whole is held as the Good, or is conceived to have emanated from an omnipotent God, mankind's acts and products are inherently imperfect in comparison. To take the example of the biblical narrative, in *Genesis* "he [God] saw that it was good".

Turning from Hebraic to Greek mythology, from the Jewish, the Moslem, and the Christian monotheisms to pantheism does not change the picture very much. When nature has effectively turned into a Pantheon, when there are distinct Gods and Goddesses associated to the sea and to mountains, to volcanoes and thunderstorms, to agriculture, commerce, or medicine, to sex and to death, to wonder at the beauty of nature is synonymous with the religious mind. It is, Acteon-like, to have had a glimpse of a deity whose divinity is so manifest, is so strikingly lovely to gaze at, is so much beyond the human sphere that the chance onlooker who ventures a single look at it is at a great risk to his sanity and to his bodily integrity. Nature is divinely beautiful. Hence, it cannot, it should not be looked at since it is populated by Gods. It is, if one thinks of it, inherently inhuman. We cannot hope to look at it directly and, if we do, then, as with the face of Medusa, we are turned into stone.

Such a sense of awe in front of natural beauties carried on, at least until the Enlightenment. As Goethe memorably put it, we shall forever be unable to synthesize a leaf or an eye. Let us only note, at this point, that he has been empirically proven to have been right – at least until now. I venture to predict that he will be proven wrong in the not so distant future. We, scientists, are well aware that any statement of impossibility is threatened with more or less immediate falsification. In our own time, we stand close to witnessing the first synthesis of either a leaf or an eye – perhaps the latter first, building on the existing technologies of genetic engineering.

To wonder, Acteon-like, at the beauties of nature is a passive, not an active emotion. But Greek mythology also included a positive reaction to the wonders of nature. It proposed a narrative of the origins of mankind, with the myth of Prometheus, who stole their fire from the Gods.

Is it not, quite a bit, the founding myth for chemistry? Helped by heat from a fire, protochemists, following the humid way or the wet way, made compounds. They reproduced natural substances. And they also made artificial compounds. Wöhler's urea synthesis was just one among many such episodes in the Promethean attempt by mankind at synthesizing a leaf or an eye – as, for that matter, any production from nature or any *artifact*.

There is irony in that word. It has come to mean the converse of its etymology. When an experiment is performed, it may become flawed by an artifact, by Nature's revenge. As in the story of the serendipitous discovery of Prussian blue, this is as if nature intruded into the laboratory. In that totally artificial environment, it reminds us of its presence, by spoiling our experiment, by ruining any potential knowledge we might have derived from it.

Nature fights back our urge for separatism, not only with artifacts, with another weapon from its arsenal too, with its very complexity. The latter translates, for us chemists, in the sheer number and variety, in the bewildering cornucopia of natural products.

Such handsome molecules! So many families of substances, all different and yet all inter-related! Such lovely biosynthetic pathways!

Even utilitarianism deems them beautiful. Consider only their assistance to mankind, in our valley of tears. Take the example of antibiotics, which are such a great help to fight disease. One gram of soil, it is said, harbors and nurtures no fewer than 10,000 species of antibiotics-producing microorganisms, such as molds. We only need to bend down and scoop up some dirt, and there you go, you are provided with new weaponry against pathogens.[6]

This is one of the most powerful arguments in favor of biodiversity. At the current rate, ca. 20,000 species are wiped out yearly from the face of the Earth, much faster than we are able to study them – for our greatest loss (not presumably, but most assuredly).[7]

The joint work of the entomologist Tom Eisner and of the natural products chemist Jerry Meinwald handsomely illustrates ecological chemistry. In this vein, mankind still partakes of the Garden of Eden and its riches. Mother Nature (another powerful metaphor) benevolently looks after our well-being. Conversely, we have an obligation to respect the environment, and to avoid despoiling it with man-made wastes. It seems a natural law, to render homage to the fragile beauty of nature. Thus, a politically-motivated Green Chemistry has made it its goal to reform and to renew industrial chemistry, achieving reactions run in water, at ambient pressures and temperatures, selective and in quantitative yield, with only water, dioxygen, dinitrogen, and very few other chemicals, as acceptable by-products.[8]

To sum-up this section: thesis A might have been crippling to the budding science of chemistry. However, due to chemistry having been from its alchemical start a Promethean enterprise, the beauties of nature have only challenged chemists even more to emulate them, and they have thus induced the beauties of chemistry. Chemistry is beautiful because it consists of natural simulacra. And chemical aesthetics are rooted in metaphysics.

Thesis B. The artificial is more beautiful

The converse of its predecessor, this thesis now assumes a turned around, and an inward-looking metaphysics: it is centered on mankind, the human animal is now put at the center and is King of creation. He is the creator *par excellence*. His designs are to be marveled at, and their very existence is admirable.

This is the notion that allows unimaginative chemists to ply their art and to synthesize new molecules almost at random, with the flimsiest of excuses: such compounds had not existed before, and thus they are bound to be interesting. Such idolatry of the artificial, as I have argued in an earlier article in this journal, leads to a most unconscionable proliferation of chemicals, which sooner or later are bound to litter the environment.[9]

Some may retort that to have re-centered science on the human, and to have jettisoned metaphysics and a priori thinking, is the very move that ushered in modern science, with the New Science of Galileo, Descartes, and Newton, and the demise of Aristotelism. How very true! But the motto according to which henceforth we stand on our own feet, and that metaphysics recedes in the mists of the past, is clearly quite a bit simplistic, and something of an illusion.

An example will suffice, that of Teilhard de Chardin, who sought to reconcile religion and science, and who forcefully introduced evolutionary thought in the Christian doctrine. His teleological notion of the human animal tending to become what he termed the Omega point of creation/evolution amounts to a re-injection of metaphysics into science.

Thesis B is not new either. Already in Greek mythology, *daidala* (such as the flying contraption used by Daedalus and Icarus, or such as the Trojan

Horse) were considered the epitome of human cunning and resourcefulness, of *metis*, as Ulysses displays repeatedly for his survival, when one reads the *Odyssey*. Chemical productions are admirable in like manner. Their very artificiality makes them a testimony to the craft, to the alliance of human hands and minds in inventing the most sophisticated masterpieces.

Consider, as an example, the art of organic synthesis. In it, the artificial outscores the natural, in two ways. A synthetic organic chemist can take for a goal the emulation of nature, and the synthesis of molecules of natural products, however complex. But the synthetic organic chemist can also go much further, and synthesize any molecule of his/her design, however fantastic it may be by comparison to the productions of nature. And, this is the second way in which the artificial beats the natural, the variety of tools available in the laboratory, the range of chemical reactions to choose from in the course of the synthesis, are vastly superior to those resorted to by biosynthetic processes. Chemical reactions made use of in metabolism are limited in number. Nature is quite monotonous and dull in its chemistry, by comparison to any modern organic chemist, however dull.

I would argue that thesis B follows from the ideological dominance of economic thought, in our day and time. We have become conditioned to accepting as laws of nature some assertions which are far from being self-evident: economic growth as the unique source of well-being; consumerism as the main engine for such economic growth; and self-regulation by the market as the most admirable mechanism. One of the distant corollaries of such economism is adoration of the chemosphere of our own design we now live in.

I am referring for instance to all these admiring statements and stances about the new materials created by chemistry, plastics and polymers in the first place. These are remarkable feats of ingenuity and of engineering; they are the modern equivalents to the *daidala* of Ancient Greece. There is a deep, philosophical sense in which an Airbus plane, say, has an identical demiurgic quality to it as Daedalus' flying machine.

Thus, thesis B has to be criticized on the same grounds and with the same mental categories as the Greeks did criticize it in their time. Thesis B smacks very much of *hubris*, and when men equate themselves to the Gods, as is well known, they tend to make fools of themselves.

If thesis B is to valued for its humanism, it is to be criticized for the conceptual confusion it encourages. To say that the artificial is more beautiful aims at being a valuation of human craft. And yet, it expresses itself as a valuation of the products of such craft. It confuses the agent and the action.

Conversely, there is feedback by which the process becomes contaminated with a category pertaining to its result, and is endowed with an essence. Thus, in claiming that, say, some polymeric material is more beautiful – more resilient, more free of imperfections, purer, *etc.* – than its natural counterpart, we tend to put uncritically the activity of chemists on an undeserved pedestal, or at least on a not fully deserved pedestal.

Thesis C. The invisible is yet more beautiful than the visible

This is a thesis for which, personally, I have a lot of sympathy. It goes squarely against naive positivism. It has this other merit, in its progressivism, to chart as it were the history of modern science, in a Whig historiographic tradition. It goes back at least to Hooke's *Micrographia* in the seventeenth century. According to this viewpoint, science makes sense of the visible and tangible world by postulating the existence of invisible entities, such as atoms and molecules.

Thus, a pencil lies there, on the table. To the chemist, it is a highly composite system. The lead in it consists of the element carbon, in its allotropic form known as graphite. The wooden part is a highly complex web of natural polymers, from the family of carbohydrates, such as lignin and cellulose. Furthermore, the chemist intuits what is absent from the mental image of the ordinary user of the pencil, this piece of matter is not an homogeneous solid, it is highly heterogeneous in any of its parts; and furthermore, both the lead and the wood are made predominantly of vacuum. A material solid is actually, to the mental eye of the chemist, a network of atoms thrown across the vacuum, as so many ropes scaling the emptiness of a gorge in the mountains.

In this manner, chemistry is endowed with a worldview both critical and constructionist – or, to use more common terminology, both analytical and synthetic. In its critico-analytical mode, chemical thought examines material samples for their component parts as atomic assemblies. Thus, it goes from bulk reality to a core reality and, in so doing, translates sensory impressions into alphanumerical symbols, as I have explained in an earlier issue of this journal: chemical analysis is a process of dematerialization, of transforming matter into written language.[10] As such, chemistry is intrinsically critical of any materialistic worldview – which is readily apparent in the violent end-of-the-nineteenth century debates about atomic theory.[11]

However, chemical science does not content itself with such a reductionist program, turning given objects into sets of invisible entities, such as seawater into point charges undergoing Brownian motion. Chemical science has a converse, constructionist program, of synthesis, *i.e.* of building material samples from scratch, whether in the total synthesis of an organic molecule from its elements, or in turning ethylene gas from an oil refinery into thin transparent films of polyethylene wrap.

Thesis C is often given axiomatic value. As such, it has been responsible for the impressive acquired momentum of the sub-discipline of mechanistic studies, which has proven itself extremely fecund in its influence on organic chemistry and beyond, to chemistry as a whole.

I will not belabor the point and sing the praise of reaction mechanisms; I have done so elsewhere, in my work as a scientist especially. Which makes me all the more at liberty to now turn around and criticize this activity and, more generally, thesis C, as belonging fundamentally to a gnosis. The Gnostic attitude, the reader will recall, consists in the membership of a sect whose essential tenet is that its members hold the truth and lead the good life, while all outsiders are hell-bent and unredeemable.

Another criticism to be leveled at thesis C is that its very radicalism encourages the return of the repressed, by every fissure or crevice, in every nook or cranny. A case at hand is that of the chemical bond which so many chemists visualize as a tight material link between atoms, differing only in size but not in essence from the hook between two cars in a train. For sure, teaching and the use of molecular models, to be dealt with in the following section, are major culprits for such a misunderstanding. But there is also the element of positivism creeping back in, probably because it has been pushed out so violently.

Thesis D. The need for visualization is unavoidable

The previous thesis C carries its puritanical penalty. We deem chemistry a science to the extent of explanations based only on invisible entities. We distrust sensory evidence in favor of instrumental data. Chemistry is no longer a science of smells and tastes and of loud reports and of flashes of color. It has become a science of spectra and chromatograms.

And yet! It would seem that, as another instance of the return of the repressed, we cannot help but need to grasp chemical reality with sensory tools, primarily visual. Under this heading come both structural formulas and molecular models. I won't say much about the latter, not to steal Eric Francoeur's thunder, I understand that he will be featured in this same issue with a contribution on this topic.[12]

The year 1814 saw the publication of 'A Letter From Mr Ampère to Count Berthollet, Upon Determination of the Proportions In Which Bodies Combine, From the Number and Relative Position of the Molecules From Which The Integrating Particles Are Composed'.[13] After a short introduction (pp. 43-44), Ampère posits the existence of polyatomic molecules in three-dimensional space. If each atom is at the corner of a polyhedron, this polyhedron will serve as the representative shape for the molecule (pp. 44-45). The relative numbers of atoms in a molecule are easily deduced from the volumes of the corresponding elements as gases, following the gas laws established by Gay-Lussac (pp. 45-47). There are five polyhedral building blocks for molecules, namely the tetrahedron, the octahedron, the parallelepiped, the hexahedral prism, and the rhomboidal dodecahedron (p. 50). Chemical combination reduces to the congruent assembly of mutually compatible polyhedra (pp. 55-71). Accordingly, chemical composition can be deduced from such geometrical considerations, and Ampère provides some concrete examples (pp. 72-86).

Ampère's paper connects explicitly with René-Just Haüy's ideas. Haüy's *molécule intégrante*, which he introduced as early as 1784 in his *Essai d'une théorie sur la structure des cristaux*,[14] was conceived as a miniscule polyhedron, since the shape of the macroscopic crystal only enlarged upon the microscopic modules within it. Cleavage of the crystal, whether an actual performance or a *gedanken experiment*, would reveal the underlying 'primitive form', which it shared with a whole family of related minerals. Ampère took over not only the concept of a *molécule intégrante* (which he termed '*particule*'), he also borrowed five out of the six 'primitive forms' of Haüy's, with the exception of the dodecahedron with triangular isosceles faces. The minor departure of Ampère from Haüy's theory was his identification of *molécules intégrantes* and 'primitive forms'.

The expression *forme représentative*, which Ampère coined, is vitally interesting because apparently redundant. Its use confirms that Ampère in 1814 was already keenly aware of the epistemological considerations he would devote himself entirely to after 1828. Had he concerned himself with the mere *forme d'une particule*, that is to say with a property intrinsic to the molecule, he would have slipped from stating a scientific hypothesis to speculative philosophy. By using the phrase *forme représentative d'une particule*, Ampère was emphasizing that the polyhedral shapes he was conjecturing were extrinsic and unessential – or not necessarily essential – properties of matter. They pertained to the description, with no guarantee as to their relevance to the object described. This is what is implied by the surface tautology in *forme représentative*. In other words, the 1814 paper was written from what Ampère would later term a cryptoristic rather than from a cryptological viewpoint:[15] discovering something hidden, rather than trying to elucidate causes for the observed facts.

I return now to Ampère's epistemological stand. First, what he does: Ampère, as we saw, chooses a hypothetico-deductive line of reasoning. He formulates hypotheses or conjectures. He then derives necessary consequences, which he pits against the observed facts. Now to what he says, which is entirely consistent (Ampère 1814, p. 47):

> whatever the theoretical reasons in support of the assumption (that the number of particles is proportional to the volume of the gases), in my opinion it is

> to be considered only as a hypothesis; however, by comparing with phenomena or with observed properties the consequences that necessarily follow; if it agrees with all the known experimental results; and if it leads to deductions which find themselves confirmed by later experiments, it will acquire a degree of probability which will approach what is known in physics as a *certainty*.

Thus, Ampère elects a hypothetico-deductive methodology and, no less important, he espouses for chemistry at least a probabilistic notion of truth.

For a number of reasons, which do not belong here, Ampère's paper did not have the influence it deserved – and the attendant epistemological considerations also became lost. This is why the notion of a molecular shape underwent a mutation, from the hypothetico-deductive to one of the many manifestations of naive realism. This is the notion that this truly fictitious entity, the molecular object, has genuine existence. The molecular object is postulated to be some sort of a contraption, associated with a given molecule, and sharing most properties of objects in the macroscopic world: a shape, a hardness, mobility of some parts relative to others, a general elasticity and bounciness, *etc.* In this case, visualization of the molecular object – too often assimilated to a molecular model of some type – is a heuristic necessity, and, at the same time, it reins in the imagination and yet may send it down the path, running after some red herring.

The molecular object shares this heuristic necessity with the attendant molecular models. Suffice it to remind the reader – and I did write on this topic elsewhere – that there is an essential playful component to science in general, to chemistry in particular.[16] A toddler will play with wooden or plastic blocks. The Montessori educational method is based in providing the child, taken to be an individual who has to grow into its own autonomy, with such a set of blocks: this is how the child, in this early version of genetic epistemology, learns about the outside world. The Montessori set serves as a simulacrum of bigger things outside of the classroom. Molecular models, which can readily be identified to Winnicott's transitional object,[17] have a very important function for chemists. It is a triple function: to the sense of touch, something to be handled in an inarticulate protochemistry of the assembly of congruent shapes; to the eye, a representation of the molecular object, *i.e.* of a reductionist idea; last but not least, a toy to play with, emblematic of the all-important ludic dimension of chemistry.

Which brings us to something very different – I do not have the space to elaborate here on the profound epistemological distance and distinction between molecular models and structural formulas. Suffice it to say that, from their inception, structural formulas were endowed with the hypothetico-deductive nature that Ampère had applied to molecular shapes. This made it possible for these formulas and for the equations they enter to become a symbolic and an iconic language for chemistry.

Are these graphic representations beautiful? Yes, undoubtedly if we deem the useful beautiful, which is one of the definitions of beauty Socrates mentions in some of the Platonic dialogs. [18] The iconic language of formulas has enormous heuristic value to chemists, who are seen repeatedly to scribble them on the back of an envelope or any old piece of paper, when they wish to predict some structural feature (short and long bonds in naphtalene, say) or the probable outcome of treating a given molecule with some reagent (what happens if I treat ethanol with chromic acid, for instance). Furthermore, chemists have evolved an internal language, a slang truly, combining use of Lewis formulas and curved arrows serving to shift electrons around, which I have argued elsewhere it is a disservice to the students to share with them – unless they are future chemists themselves.[19]

To sum up this section: the visualizations chemists are prone to give themselves of invisible entities are treacherous, not only as oversimplifications, but because they leave out many essential characteristics of molecules – such as to limit myself to just one, electronic delocalization over the whole molecule.

Thesis E. The beauty of chemistry stems from an inner logic

Any chemist works with the confidence that the field is not only well charted but also coherent and self-consistent (these last two are not totally synonymous). Moreover, there is the supplementary notion of autonomy of the discipline, from physics.

And yet, if this chemist is questioned about thesis E, the fall-back position is likely to be that ultimately the workings of chemistry are reducible to a few physical laws and, since physics is self-consistent, chemistry has to be as well. In other words, chemists do not have an explicit argument at the ready as justification for the presence of a non-contradictory inner logic.

Furthermore, most chemists in actual practice behave in a rather schizoid manner, making use of intrinsically contradictory formalisms. They will use, almost interchangeably, representation in terms of localized bonds (so-called valence bonds) and molecular orbital theory, which implies full electronic delocalization.

Should we then exclude thesis E from consideration? After all, it might be argued that it is a weak rather than a strong thesis. It might be construed as the statement 'any subject of study has an inner logic to its practitioner', which might apply, say to the art historian. If this were the case, we would be dealing with a corporatist illusion borne from habit, and having nothing to do with the existence or lack of a self-consistent logical backbone in chemical science.

And indeed chemistry, watched in its habitual practice, is predominantly an inductive science. Chemists perform experiments, they collect data, and they take a pragmatic attitude toward theoretical analysis of their data. They are not very demanding towards theory and its being part of a coherent corpus. Often, they will content themselves with an ad-hoc theory. Why is there such a disregard for the inner logic of the field, contrasting with the attitude of physicists? Physicists tend to be much more federally minded than chemists are.

Assuredly, chemistry is not reducible to a few axioms or principles from which the whole science could be deduced. Yes, it is true that, in principle, the Schrödinger equation or the Pauli Principle subsume nearly all of chemistry. However, such a deduction remains a practical impossibility in most cases. Moreover, when chemists rejoice in the beauty of their science for the underlying logic, they are not necessarily thinking of such a priori principles.

The reason for their attitude is clearly to be found elsewhere. The language of chemistry is what gives it its inner logic. And chemists bask in such self-assurance because of history. They started writing and using structural formulas in the 1850s. Only in the 1920s, with the advent of quantum mechanics, was the basis for this empirical practice by the chemists finally understood, on their own terms, by the physicists. Likewise, a formula such as that of benzene was first written by Kekulé in the 1860s, and it was quickly adopted by the whole profession, starting with industrial chemists active in the preparation of dye molecules. X-ray crystallographers were able only in the 1920s and 1930s to confirm the correctness of Kekulé's formulation and his prediction of the equalization of carbon-carbon distances in the benzene molecule. Other, more direct, determinations of the benzene ring as a regular hexagon intervened yet later.

It is this iconic language of molecular formulas upon which chemists base their optimism – an act of faith, truly – in the inner logic and hence in the resplendent beauty of their science.[20]

Thesis F. The beauty of chemistry stems from its unpredictability

Chemists also pride themselves on theirs being an experimental science. An experiment is devised in order to test an idea. The meaning of these words, 'to test an idea' is not obvious. It may be taken to mean the refutation of that idea, its range of applicability, its pertinence, *etc.* I am only mentioning such polysemy in order to remind the reader of the epistemological complexity of experimentation.

But let us take a concrete example; it will help me to make a point. Suppose that, in the course of a multi-stage synthesis, and as a truly routine action, the need arises for protection of an alcohol group. Nothing could be more trivial or standard. And yet, in this particular case, the standard procedure fails – for no good reason. The chemist has to find a way, some trick to circumvent the difficulty which has suddenly arisen. Especially if this is a chemist blessed with curiosity, at some later time the obstacle may become apparent; and the chemist will have understood what had gone wrong.

The point is that matter is not infinitely docile or pliable. Nor is the art of the chemist infinitely powerful. Each single experiment, however predictable the result, is fraught with uncertainty. A reaction which is known to run smoothly in solvent A will give only poor results, if it runs at all in solvent B – which for some reason the chemist is beset with.

It is not only the case that even routine experiments will not yield the expected results. More interestingly, there are frequent occasions when the experiment works, but shows totally unexpected results: chemistry is a science in which one learns from experiments. Young chemists learning their craft do so from supervision by a senior chemist. But they do learn also, perhaps even more, from what nature will be teaching them.

I claim that chemistry is, to an important degree, the realm of the unexpected, serendipitous result; and that chemical science consists, to some extent, in learning how to prepare oneself to welcome the unexpected. I shall also claim that the unpredictability of chemistry differentiates it from another experimental science, such as physics; while it makes it closer to biology, likewise likely to surprise its investigator.

To return to aesthetics, the unpredictability I have just been focusing on makes me opt for Socrates' definition of the beautiful in Plato's *Gorgias*, as the union of the pleasing with the useful. Since any scientific observation, or even discovery, tends to be applied as a tool, as a new tool toward subsequent research.

Thesis G. Any change is handsome on account of its invariant elements

This particular thesis addresses the definition of chemistry as a science of material transformations. The human mind encompasses change, provided that it shows regularities. Even chaotic change was analyzed theoretically, in recent years, as originator of regular patterns, which partakes of the same mental urge to seek order, even in situations disruptive of any prior organization.

And indeed an important chapter of chemistry is the typology evolved for the most frequent and useful chemical transformations. It offers classifications of reactions, presented in textbooks and taught to students, under categories, such as substitutions, additions, eliminations, rearrangements, *etc.*

One can also see the chemical mind busily ordering chemical transformations into arrays, from the linguistic metaphor. According to it, atoms in a molecule are like letters in a word. The three-dimensional disposition of atoms in a molecule specifies uniquely this chemical entity, just as the linear sequence of letters defines a word. Hence, a chemical transformation is analogous to the scrambling of letters in a word, which turns it into another word.[21]

Accordingly, it is not surprising if students of such chemical transformations often focus on the elements left unchanged – on the invariants. An example, which is rather ordinary at that but historically important since during the first half of the nineteenth century such invariance was already recognized, is the chemical group, *i.e.* a group of atoms (such as a carbon bearing three hydrogens), surviving most chemical reactions unscathed.

What is more to admire of the beauty of a transformation: what is changed beyond recognition or what is left unchanged? In human life, as people age, they often come to appreciate both sides of the coin, the changes in their daily life wrought by time, and the few areas or items which somehow seem to have remained immune from the attacks of time. The pieces of slate we learned to write on, as children in my generation, are long gone. But books for reading endure, even in our electronic age. Chemical reactions offer the same pleasure to our schizoid attitude toward change, the love of change *quia* change, and the affection for the endurance and permanence of certain entities in the face of change.

Which brings up what might be hailed as the foremost discovery of chemical science during the twentieth century: conservation of orbital symmetry in electrocyclic reactions; and the attendant selection rules, as they came to be formulated by Robert Burns Woodward and Roald Hoffmann.

This whole section is sustained by its inner contradiction, by the tension between change and invariance, between motion and stasis. Is it not one of the topos of the philosophical mind, after all, to keep pondering old paradoxes, never to be solved, such as that of Achilles and the Tortoise?[22]

Thesis H. The beauty in any change is the fleeting instant

In the 1960s, theaters on Broadway showed a musical comedy entitled 'Stop the World, I Want to Get Off'. This might be taken as a motto for chemistry. The intellect is dull and very slow, when it wishes to analyze, to look at each individual piece in a jigsaw puzzle in order to make sense of it. Equivalently, problem-solving, which often is what science reduces to, has for its first step the careful consideration of the data, before a solution jumps to mind (in the best of cases).

Indeed, chemical science, when it addresses chemical dynamics, also has this respectable urge at stopping the world, in order to give it a good, hard look; somehow turning time into a picture of space. Here, the analogy is from the movies, and the phrase is 'a frame frozen in time'. Any chemical transformation amounts to a linear time sequence – we are back to linearity, as that of letters in a word – of such instantaneous frames. Nowadays, predominantly using ultra-fast laser pulses, such as in the work which won Ahmed Zewail his Nobel Prize, we are down to windows as short as a femtosecond. We are able, nearly but not quite, to look at chemical reactions in real time, as the phrase goes.

There is an aesthetic component, for sure, in such an activity. To put it in a nutshell (how appropriate here), it stems from the alluring excitement of voyeurism, all the more forbidden that it occurs in a glimpse, for such a fleeting instant.

To continue with aesthetics, I submit that the above corresponds to Kant's assertion, to be found in § 6 of his *Critique of Judgment*: "It is beautiful what pleases universally without concept." This proposition has, in my eyes, the dual merit of a refutation of relativism (stating dogmatically that one is unable to discuss any matter of taste) and hence to put aesthetics on a firm basis; and of sparing these two related feelings, regarding beauty, and regarding the sublime, continuing to imbue them with all the opacity of poetical intuition. The universal character of the assertion 'this is beautiful' is irreducible to rational analysis, of the type of the logical judgment by which we convince ourselves that a given mathematical demonstration is just and true. The absence of any possible conceptualization of the beautiful, which prevents us from defining it – the stumbling block for both Socrates and Plato –, is characteristic of aesthetic judgment. It accounts for its singularity.

Thesis I. The beauty of chemistry is that it is a science of the complex

To state the paradox cogently, complexity is appalling and yet it can be appealing. It calls for understanding in our context, that of the bases of chemical aesthetics, since chemistry is very much a science of the complex. There are very many different chemical entities. The number of known molecules alone verges on 20 millions. Any chemical system or reaction is subject to multiple parameters, such as pressure, temperature, concentrations and activities, nature of the solvent, *etc.* An impurity present only at the level of traces can totally change an outcome.

Where is the beauty then, in such bewildering, mind-boggling complexity? In the mind, in the ever renewed feat by which the intellect, makes itself able to unravel extremely complex situations. There is a great satisfaction in making sense. Akin to a chemical change, to a *Gestalt* switch too is when we see our way out of a tangled web of variables and parameters and equations. The intellect prides itself in making sense of the complex. The same kind of an aesthetic element is present in a detective novel, where we derive pleasure from identifying with the hero who untangles a complex knot of events and characters.

It is no accident if chemists use the word 'complex' to denote certain kinds of molecules – actually neither simpler nor more complex than other types. Chemistry relishes complexity. To use this example of complexes, for instance coordination complexes, complexity here is essentially a matter of large numbers. There exists a very large number of complexes with the general formula ML_6, where M is a metal and L is a ligand: dozens of possible choices for the central atom M, hundreds of choices for each of the six ligands L; which translates into a total number of species in the order of magnitude of tens of thousands of billions – of which of course only a minute fraction can have been made and isolated and studied.

Which brings up another point. In order to achieve a full understanding of complexes of the general type ML_6, chemists need only to prepare and to study less than perhaps 0.01 percent of one percent. These compounds are more than enough to make us able to predict with utter confidence the precise geometry, the reactivity too of any of the still unknown complexes belonging to this set.

You have there the beauty of complexity, in the strong sense: it does not deter intelligence, it does not prevent the advancement of knowledge and of understanding.

Thesis J. The beauty in chemistry is in that it is a science of the simple

A good philosophical question, when considering chemistry, is that of the relationship between simplicity and purity. Chemists harbor this ingrained notion that, after extensive and proper purification – of the reagents, of the solvents, of the flasks, *etc.* – everything will be simplified. Reproducibility of the procedure will ensue. It will then, and only then, become feasible to attempt an explanation.

An aesthetic feeling delves there. It is akin to the Pythagorean reverence for numbers. Probably because the systems they deal with are so devilishly complicated, chemists have a cult for simplicity.

And indeed the Pythagorean spirit informs and underlies much of chemistry. Consider only the shape of molecules: a naive outside observer might guess that anything goes, that a molecule can exist under any odd shape (as indeed it does). And yet chemists, from times immemorial, have tended to reduce such a cornucopia of molecular shapes to the highly restricted set of five, only five Platonic solids: the tetrahedron, the cube, the octahedron, the dodecahedron, and the icosahedron.

Why are chemists thus obsessed? Why does the regular arrangement of points on a sphere exert such quasi-religious fascination? One might tell a history of chemistry using only, not a time line, but a timeless line, chronicling the hold of Platonic solids on the chemical imagination: Ampère, defining with polyhedra the notion of a molecular shape; Alfred Werner, bringing coordination complexes into the realm of chemistry, and reaping so many fruitful conclusions from consideration of just one of the Platonic solids, the octahedron; closer in time to us, the VSEPR rules of Gillespie-Nyholm, relating molecular shape (and the attendant polyhedron) to the coordination number; the synthesis of hydrocarbons in the shape of the Platonic solids, whether pertaining to cubane chemistry which Philip E. Eaton so beautifully opened up, or Leo Paquette's synthesis of dodecahedrane; or yet, the notion, now central to molecular biology, of an icosahedral virus… I need not go on. There is a dominion over chemistry of the idea, of the simple and simplistic idea, of Platonic solids, of Platonic shapes, as encompassing all of chemistry.

Thesis K. By way of conclusion:[23] A new contemporary art has been born

From time to time, museums and libraries exhibit anatomical drawings and engravings from the time of the Renaissance. Such images, if handsome to look at, also please the mind. They give a sentiment of plenitude, since they make us witness a now lost unity of art and science, at the time of the birth of modern science.

Could it be that a similar opportunity is offered to us nowadays? We are witnessing another aesthetic revolution, which also stems from images of science – and those are anatomical depictions too. The second half of the twentieth century has been the period for the multiple appearances of brand-new lessons in anatomy. Not that they derive from a new genre, they continue being informed by requirements for analysis, accuracy, and high legibility. They continue to dissect and separate interwoven components.

Their scale is different, though. Their subject matter occupies, within the realm of the microscopic, a new space, that of the nanoscopic and of those nanorobots, the enzymes, whose dimensions are expressed in nanometers.

About ten thousand protein structures populate already this world. For being nanoscopic, it has nevertheless three dimensions, just like the ordinary, macroscopic space of our lives. Each of these protein molecules is made up of thousands, if not tens of thousands atoms, arranged into a unique, precise and distinctive topography. Data banks accessible through the Web store all of their coordinates. Thus, any of us can readily visualize shapes which had never been seen before by anybody's eye. Moreover, each one of us is free to opt for a representation or another, selected from the dozen or so options provided by existing software – and, I venture to predict, following the whim or the fantasy of an artist, in the not-too-distant future.

Where is such an art headed, with its content being a three-dimensional sculpture, representative of a molecule? This is harder to predict. An artist may project on such objects colors, lightings or shadings, material illusions or phantom-like evanescences, and quite a variety of surfaces and skins.

Only well-informed scientists enjoy at present the privilege of rejoicing in such images. Through the Internet, it is easy to interrogate a data bank such as the PDB (Protein Data Bank) at the Brookhaven National Laboratory in the USA, and to download one of these structures, for display on one's computer screen. We are put into a similar position to one of Jules Verne's character, Wilhelm Moritz, in being given our own, private movie theater. Rather than the re-enacting of a beloved diva singing an aria from an opera, we are treated to the sight of eerie shapes, just as mysterious, just as sublime. We are free to make them move around, tumble around this or that axis. We are free to zoom into them, for inspection of even their most intimate parts. In this manner, we are put in the position of an apprenticed painter or sculptor, drawing from a nude model in an academy. Clearly, I am not shying away from an anthropomorphic metaphor. The resources of computer science allow already one or two dozens representations, in standardized mode, all distinct, sometimes quite different from one another, for any given biomolecule.

Abstract art and figurative art are often contrasted. The latter holds itself to provide, just as science does, a representation of an objective reality, posited as external to the artist. Abstract art bypasses reference to reality. A painting or a sculpture becomes the object of its own representation, with which it identifies. This novel art, yet to be born, of the nanoscopic architectures of life, derives from scientific studies of nature. Thus, it is realist. Nevertheless, it gives us to see the never-yet-seen – to be more accurate, it offers to our surprised sight views of the invisible. These shapes are more miniscule, by about ten orders of magnitude, than the usual objects in our daily life. One may speak here of a hypotrophy of eyesight. Only an instrumentalized eye, through the resources of X-ray diffraction or nuclear magnetic resonance, can access such wonders.

Furthermore, these nanoscopic molecules unveil themselves to us in multiple ways, all arbitrary, each at the leisure of their demonstrator who happens to be also the viewer. In so doing, this new abstract art links with the most spectacular successes of lyric abstraction or of abstract expressionism. Synthesis of the figurative and of the abstract, this evolutionary limb has to be an extension of the pictorial art of the twentieth century. Will it be the art of the twenty-first century? For certain, provided that it recruits its artists, which assumes that there is some extent of reconciliation between art and science.

This will then be my conclusion: I call for a great exhibition displaying this altogether new art form. [24]

Appendix: Bibliographical orientation

Below are a few pointers to some texts which I have found as highly relevant to the questions raised in this paper.

Socrates, who was no fool, and who denied the existence of an essence of beauty – any object might be construed, he said, as beautiful or not, depending on the circumstances –, when asked to define the beautiful was likely to answer 'the useful'. The Platonic dialogues are one evidence. There is another source. Equating the beautiful with the useful may indeed well have been authentically Socratic rather than Platonic. Xenophon (*Defense of Socrates, Memoirs of Socrates*) also reports it. (C. D. C. Reeve [ed.], *The Trials of Socrates. Plato, Xenophon, Aristophanes*, Hackett, Indianapolis 2002.)

If we jump now to the end of the eighteenth century, Immanuel Kant (*Critique of Judgment* [1790], Hackett, Indianapolis, 1987) presents an Enlightenment view of artistry. In intellectual history, it is contemporary with the fine arts being defined as such, in works such as Diderot and D'Alembert's *Encyclopédie*. Kant contrasts the beauty of art works with that of natural objects. Intentionality is for him the distinguishing criterion. Any human artifact first existed as a project. Thus, a mental representation preceded its actualization. Accordingly, any art piece carries with it a lingering trace of its creation.

Let me note in passing that the Kantian criterion does not necessarily exclude a representation, of a protein structure say, from being an art piece.

In his pitting natural against man-made beauties, Kant seems to opt for the former nevertheless. If I may quote from § 42 of the *Critique*, with its altogether pre-Romantic tone:

> If a man with taste enough to judge of works of fine art with the greatest correctness and refinement readily quits the room in which he meets with those beauties that minister to vanity or, at least, social joys, and betakes himself to the beautiful in nature, so that he may there find as it were a feast for his soul in a train of thought which he can never completely evolve, we will then regard this his choice even with veneration, and give him credit for a beautiful soul, to which no connoisseur or art collector can lay claim on the score of the interest which his objects have for him.

Notice the emphasis on the "feast for his soul". Obviously, to Kant, the aesthetic experience has quasi-mystical overtones. And it is disconnected from the everyday.

Nelson Goodman rejected the Kantian criterion of intentionality for deciding whether something is a work of art. He chose to anchor aesthetics in cognitive and semantic values, instead of emotional ones. Goodman identified five properties or symptoms identifying a work of art. These are (i) syntactic density, *i.e.* a grammar conveying extremely detailed shades of meaning; (ii) semantic density, by which he calls attention to the wealth of expressive symbols present; (iii) the relative repleteness, *i.e.* the lack of semantic redundancy, the fact that a work of art is highly effective in the means it gives itself for expressing meaning(s); (iv) exemplification, by which symbols stand for a whole class of elements; and (v) the multiplicity and complexity of references present in the piece. (N. Goodman, *Languages of Art*, Bobbs-Merrill, Indianapolis, 1968; *Ways of Worldmaking*, Hackett, Indianapolis, 1978; *Of Mind and Other Matters*, Harvard University Press, Cambridge MA, 1984.)

Theodor W. Adorno showed great interest in aesthetics, the topic of his last book, *Aesthetic Theory*, left unfinished at his death in 1969. He took a demanding view of aesthetic experience. It had to be disconnected, he was convinced, from the mere pleasurable feelings which bourgeois hedonism contaminates it with. Experiencing an art piece, for him, required self-abnegation. It demanded an effort to immerse oneself into the full presence of the art piece, with its opaqueness and multiplicity of meanings.

Kant-like in this respect, Adorno had also heightened sensitivity for natural beauty – which of course is a major topic in my paper. He saw man as the great tamer and as the great destroyer of nature (not an original view). However, Adorno proposed this astute ploy: that art serves as a refuge, that it becomes a substitute for the nature which mankind has all but eradicated. "The concept of natural beauty rubs on a wound", he wrote, which I hold to be a deeply perceptive remark. (Th. Adorno, *Aesthetic Theory*, Routledge, London, 1984).

Hans-Georg Gadamer also made a frontal attack against bourgeois perceptions and 19th-century aestheticism (*L'art pour l'art* doctrines), since they excise an art piece from its socio-historical context. Any artwork finds its foremost meaning within an historical continuity. To enjoy it with immediate sensations only is to rob it of its wholeness, to fragment it into a manifold of individual experiences. Such behavior on our part shields us from penetration, from the deep personal changes which an authentic artistic experience entails. (H.-G. Gadamer, *Truth and Method*, Crossroad, New York, 1982.)

Pierre Bourdieu was even more radical (more superficial too) in his critique of the essentialist fallacy, consisting in the immediate experiencing of an art piece for its so-called 'aesthetic value'. He called attention to such an attitude being both historically dated and socially marked. He called attention to Kant's disinterestedness criterion being primarily a middle class evasion of the realities: to thus experience an art piece is to set an artificial distance from the world, just as the middle class is anxious to differentiate itself from manual labor, from the daily necessities of production. (P. Bourdieu: 'The Historical Genesis of a Pure Aesthetic', in: R. Shusterman (ed.), *Analytic Aesthetics*, Blackwell, Oxford, 1989; *La distinction, critique sociale du jugement*, Editions de Minuit, Paris, 1979.)

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10 Laszlo, P.: 1998, 'Chemical Analysis as Dematerialization', *Hyle*, **4**, 29-38

11 See however Görs, B.: 1999, *Chemischer Atomismus: Anwendung, Veränderung, Alternativen im deutschsprachigen Raum in der Zweiten Hälfte des 19. Jahrhunderts*, ERS Verlag, Berlin.

12 [Editorial note: Eric Francoeur will contribute to this special issue with a paper on 'Necessity or Pornography? Photorealism in Molecular Representation' to be published in *Hyle*, vol. 9, no. 2.]

[13] Ampère, A.-M.: 1814, 'Lettre au Comte Berthollet', *Annales de Chimie et de Physique*, **XC**, 43

[14] Haüy, R.-J.: 1784, *Essai d'une théorie sur la structure des cristaux appliquée à plusieurs genres de substances cristallines*, Goguée & Née de la Rochelle, Paris.

[15] Ampère, A.-M.: 1834 & 1843, *Essai sur la philosophie des sciences, ou exposition analytique d'une classification naturelle de toutes les connaissances humaines*, Bachelier, Paris.

[16] P. Laszlo: 2000, 'Playing with Molecular Models', *Hyle*, **6**, 85-97.

[17] Winnicott, D.W.: 1957, 'Pourquoi les enfants jouent-ils?', in: D.W. Winnicott (ed.), *L'enfant et le monde extérieur*, Payot, Paris, pp. 123-128.

[18] For instance, Plato, *Gorgias*, Part 5: Socrates says "Let me ask a question of you: When you speak of beautiful things, such as bodies, colours, figures, sounds, institutions, do you not call them beautiful in reference to some standard: bodies, for example, are beautiful in proportion as they are useful, or as the sight of them gives pleasure to the spectators; can you give any other account of personal beauty?" (Plato: 1987, *Gorgias*, Hackett, Indianapolis).

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[20] Laszlo, P.: 2001, 'Conventionalities in Formula Writing', in: U. Klein (ed.), *Tools and Modes of Representation in the Laboratory Sciences*, Kluwer, Dordrecht, pp. 47-60.

[21] Laszlo, P.: 1998, 'Belabouring the Obvious: Chemistry as Sister Science to Linguistics', in: P. Janich & N. Psarros (eds.), *The Autonomy of Chemistry*, Königshausen & Neumann, Würzburg, pp. 47-60.

[22] A remark of a referee leads me to emphasize that indeed chemistry shows beauty, not only in the structures it studies (and renders static for that purpose), but also in their dynamics. Peter Mitchell has contrasted the former (scalar quantities, which he terms statids) with the latter (vectorial quantities, which he terms fluctids). Such fluctids are involved in life processes. Ionic transport across cell membranes is an example. I recall how it held my coworkers and I mesmerized with its elegance and beauty, when we were studying it, using sodium-23 nuclear magnetic resonance as our main tool.

[23] A comment may be in order regarding the format of this article, as a series of commented propositions, some of which are apparently mutually inconsistent. I have chosen it, from experience and instinct both, as most proper, adequate, congenial too, for chemistry. Yes, I do hold all these assertions to be simultaneously true.

[24] Laszlo, P.: 2002, *L'architecture du vivant*, Flammarion, Paris.

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