# Nanochemistry: What Is Next?

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In every new scientific endeavour it is always important to ask, after the dust has settled, questions such as: Is this new area a field or a just a trendy phenomenon? Is it a paradigm shift or just a stepping stone? What are the contributions of this research to science? Has it delivered on its scientific and technological promises? What's next, and where do we go from here? What follows is an opinionated perspective on what could be the answers to these questions; it is a perspective of somebody who has seen the field rise and of somebody else who has got his hands dirty with it. The intent is not to prophesize but rather to incite discussion and reflection in the community about the future of this field, which finds itself at a crucial turning point of transitioning from being the ''next big thing'' to blending into the woodwork.

The beginning of nanochemistry is undoubtedly a controversial topic. One could contend that, as in most things human, there is never a real beginning of a field, as every field is rooted in previous discoveries. We also contend that it was only in the early 1990s that, from a vast but scattered dispersion of experiments and ideas, the community ''crystallized'' a conceptual blueprint for nanochemistry, a new direction for synthetic chemistry beyond atoms and molecules — one that focused on a chemical approach to groups of these fundamental chemical building units, fashioned at a length scale between them and the bulk material. After many years, this can be still regarded as a working definition for nanochemistry.[1,2]

In the broadest sense, nanochemistry employs the tools of synthetic chemistry and materials chemistry to make nanomaterials with size, shape, and surface properties that are designed to evoke a specific function and orchestrated to target a particular end use. These building blocks of nanochemistry may have value on their own, such as a nanocrystal single-electron transistor, or instead it may be groupings of these building blocks that are relevant, being self-assembled into structures or patterns that offer a clear function and utility, for example, a semiconductor nanowire electronic circuit.

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DOI: 10.1002/smll.200900113

In the beginning, the excitement of nanochemistry was in the size- and shape-dependent properties of nanomaterials, which were perceived as a treasure trove of opportunities for the bottom-up chemical control of the behavior of materials. This approach represented a dramatic shift from the traditional top-down nanofabrication methodology based on carving out nanostructures from planarized bulk materials by using photon, electron, atom, and ion beams practiced in engineering and physics for many decades.

In those early days, the great appeal of a synthetic approach to nanomaterials was the ability to create nanoscale building blocks of any composition: inorganic, organic, polymeric, biological, and hybrid versions thereof. Chemistry was uniquely placed to achieve nanometer-precise command of the size, shape, surface structure, charge, and functionality of these building blocks. Moreover, this set of skills was setting the stage for the control of their self-assembly in a massively parallel fashion to create designed architectures that exhibited hierarchical structure and function to enable a purposeful application.

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Since then, nanochemistry has been recognized by textbooks, funding agencies, and teaching programs across the world. But are these the arguments that make nanochemistry a ''field'', whatever the meaningfulness of such a ''title'' is? We don't think so. After all, has nanochemistry delivered on its scientific and technological promises? After billions of dollars of investment in academic, government, and industrial laboratories, maybe it is time to ponder: Where do we go from here?

History shows that disruptive conceptual breakthroughs in science enable revolutionary developments in technology that improve the human condition.[3] What is, then, the disruptive conceptual breakthrough behind nanochemistry? We believe that the major conceptual contribution of nanochemistry, besides the broadening of the conceptual basis of chemistry to the new ''synthetic degrees of freedom'' of size, shape, surface, self-assembly, and bionano, lies in the interdisciplinarity that it has imprinted in its neighbouring fields (Figure 1). This transformation can probably be considered as the greatest success story of nanochemistry, as it has brought the science, engineering, biology, and medical disciplines together in a unique way to dream up and create new materials that solve problems — an interdisciplinary but chemistry-driven approach

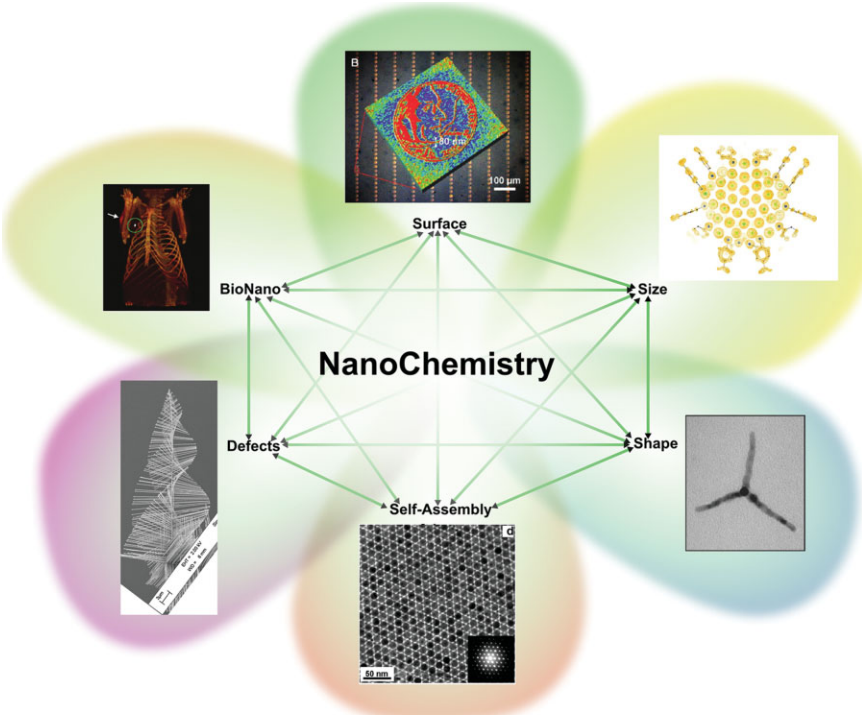


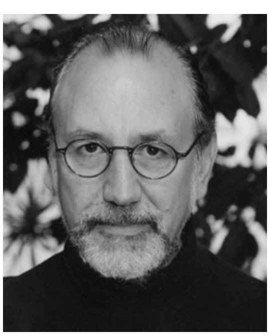

**Figure 1.** This diagram illustrates a proposed conceptual framework for nanochemistry, which has emerged with the evolution of the field. The new "degrees of freedom" of surface, size, shape, self-assembly, defects, and bionano are globally connected. The connections are what can be considered to define nanochemistry as an area of research. Clockwise from the top: images reproduced from Reference [4], with permission from Reference [5] (copyright 2007, American Association for the Advancement of Science), with permission from Reference [6] (copyright 2003, Nature Publishing Group), with permission from Reference [7] (copyright 2006, Nature Publishing Group), with permission from Reference [8] (copyright 2008, American Association for the Advancement of Science), and with permission from Reference [9] (copyright 2006, Nature Publishing Group).

to challenges. The contribution of nanochemistry might thus be more in the research methodology that it has stimulated than in the results it has since provided.

Nowhere can this be better appreciated than in the contributions of nanochemistry to interdisciplinary scientific advances exemplified, among others, by: i) enhanced-efficiency solid-state batteries,[10,11] fuel cells,[12] photovoltaics,[13] lighting systems,[14] and thermoelectrics[15] aimed at clean, low-cost energy generation, ii) nanoelectronic,[16] nanophotonic,[17] nano-optical,[18] nanomagnetic,[19] nanofluidic,[20] and nanomechanical[21] devices, iii) chemical and biological detectors with improved sensitivity, faster response times, and better selectivity,[22] iv) catalysts and photocatalysts,[23,24] v) nanomotors driven by chemical and biochemical fuels,[25,26] and vi) a myriad of nanomedical breakthroughs such as cellular and organ imaging in vivo,[9,27] treatment or cure of different forms of cancer,[28] and targeted drug and gene delivery.[29]

While these advances are indeed encouraging, there is an increasingly common feeling that nanoscience has not yet delivered on its initial promises, especially from a technological perspective. Although it is true that the world is seeing the first "nano-enabled" products, most of the really interesting and potentially disruptive devices are still "trapped" in academic and start-up laboratories. There are many reasons for this perceived delay, none of which are related to the real promise of the field.

On the one hand, it is a widespread opinion that unrealistic promises were often made, especially in terms of timeframes. Bringing an innovative process into an industrial pipeline can take years in itself. On the other, we feel that attention has been too focused on demonstrating devices and functions, with so called proof-of-concept examples that in many cases end up proving very little in terms of technological potential. It is well known that to publish nanochemistry work in prestigious journals often requires the demonstration of "some sort of device." Little concern is devoted to whether the device is *really* needed. What is more often needed is a consistent and systematic approach to the understanding of the issues behind the current problems of reproducibility and reliability in nanoscale devices and materials. Promoting this focus would mostly be up to us scientists and our fellow editors, as we constitute the body of referees who determine what gets published and what gets funded.



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Another issue might lie in the widespread tendency of not publicly disclosing in enough detail the limitations of our findings. The reasons are widely understood and have more to do with necessity than with a scarce understanding of ethics. But the consequences of this behaviour are multiple. For nanochemistry, as well as for most other "hot fields," discussing the limits of one's research can end up damaging one's "status" and potentially one's success as a grant applicant. But it is a behavior that sabotages progress as it deprives young scientists of an understanding of what are the issues to tackle. One generally needs to stay in a field for years before one can have a clear understanding of its inconvenient truths. Richard Feynman, the perceived founder of nanoscience with his "There is plenty of room at the bottom" lecture, discussed just as powerfully the importance of being brutally analytical and open on the limitations of our results.[30] It is not by chance that a widespread half-joke among chemistry graduate students regards the phenomenal impact that a journal on failed experiments would have.

What we are learning from a decade and a half of nanochemistry research is that nanochemistry is a "provider" of a myriad of nanoscale building blocks, an "enabler" of nanotechnology, and a contributing "founder" of future bottom-up nanofabrication, the success of which will be contingent upon being able to synthesize and assemble single-size and -shape building blocks with controlled surfaces into functional nanostructures and integrate them into useful and defect-tolerant nanosystems.

## Nanochemistry Challenges

So it is time to ask: What's next and where do we go from here? Nanoscience and nanochemistry take specific strength when they accept the confrontation with the grand challenges of humanity. It is a visionary power that is now blooming again, owing to necessity and opportunity: the vision is that nanoscience can, in this moment of great need for world-wide solutions, provide answers and help society in unprecedented ways. While hype is a common "infestation" of new research developments like nanotechnology, vision is not its synonym; vision is the imagining of where we are heading — hype is the delusion of where we already are.

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What one can do now, in a very specific way, is to choose how to contribute to the grand challenges of tomorrow; one's very own vision of oneself as a professional scientist. We have thus compiled a short list, in no specific order, of what could be the *scientific challenges meaningful to nanochemistry* for the next decade or so. We selected just those areas in which we feel that nanomaterials could provide disruptive and novel solutions and not just incremental improvements over old technology. This list is not cast in stone; it is based on our opinion and personal experience, and is thus likely to miss important developments. We feel, though, that it is important to think about what is important, and where we stand, for the very simple reason that time, funding, and human resources are limited. We should, then, have some sense of what our priorities might be.

For students reading this commentary, even those not intending to become fully fledged nanoscientists, the knowledge of these challenges and of how nanochemistry can contribute to them will be fundamental for you, whatever direction your career takes.

### 1. Nanodiagnostics

a. Nanomaterials have a size that makes them viable as probes in organisms.
b. Each nanomaterial probe is generally more efficient than a single contrast-agent molecule by orders of magnitude, which implies a higher imaging resolution, a lower use of targeting vectors, and a smaller saturation of the targets.[31]
c. They can have physical properties (e.g., plasmon resonances) radically different from traditional molecule-based probes.[32]
d. They can have a radically different biodistribution, depending on their size, surface charge, and shape.[33]
e. They can be judiciously tailored (size, shape, surface charge, and chemistry) to different conditions without requiring complicated organic chemistry protocols.
f. They can be produced cheaply from readily available inorganic materials, which makes them amenable for use and production in low-resource settings.

### 2. Nanotreatment

a. In addition to the points mentioned under Nanodiagnostics, nanomaterials provide new mechanisms for the treatment or cure of certain diseases that were not available before (e.g., magnetic hyperthermia[34]).
b. Nanoscale constructs can employ new drug-delivery mechanisms completely different to those of molecular-scale delivery vehicles.

### 3. Nanolocomotion

a. The motion of nanoscale objects in liquids is radically different to that of macroscopic objects and is dominated by viscous forces and characterized by a very low Reynolds number (ratio of inertial thrust to viscous drag).[35]
b. The use of nanomotor theory and simulations to understand the coupling of motion to the hydrodynamic bath and to elucidate the mechanism of propulsion could provide a theoretical underpinning for experimental investigations.
c. Chemically powered nanomotors, control of speed and direction, dynamic visualization, and attachment and

delivery of payloads are important steps towards purposeful nanomachines that perform tasks.

## 4. Nanophotonics

a. The behavior of light in nanostructured media is significantly different to that in vacuum.[36,37]
b. The use of material properties (plasmonics) or architectures (metamaterials, photonic crystals, granular materials) will change the way we manage and use the interaction of light with matter.
c. Almost all of the world's energy will be provided by photons.

## 5. Nanocomposites

a. Years of research have been put into the design of single well-defined building blocks — not nearly as much research has been put into making and studying bulk materials made from those building blocks.
b. New and unexpected phenomena can arise from materials made of mixtures of well-defined nanoscale building blocks.[38]

## 6. Nanomaterials for Developing Nations

a. Nanomaterial-based devices often lack efficiency and reliability but can excel in terms of cost as they do not necessitate top-down technology.
b. These characteristics bode well for use in low-resource settings in which efficiency and reliability are not key but cost is the bottleneck.

## 7. Nanoscale Junctions

a. The development of increasingly well-defined nanomaterials will enable the understanding of electron transport in nanoscale junctions (molecular to nanoscopic).
b. This target is fundamental for the exploration of the scaling limits of electronics.

## 8. Nanocrystallization

a. We mostly do not understand the process of nucleation and growth.[39]
b. We still do not know how to make perfectly monodisperse nanocrystals, which would instantly solve most of the problems related to the use of nanomaterials in devices (e.g., heterogeneity, batch-to-batch variations, etc.) and bioapplications (e.g., toxicity screening).

Nanochemistry is, indeed, just one of the enablers on the nanotechnology roadmap[40] that paves the way forward. The other players, which were intentionally not covered in this commentary as the focus was a chemical approach to nanomaterials, include:

- Nanofabrication: suite of top-down lithographic techniques
- Nanotools: defining the structure and properties of nanomaterials
- Nanoimaging: visualizing nanostructures
- Nanomanipulation: moving, positioning, interconnecting, and contacting nanostructures

## Nanochemistry Crystal Ball

In this final section we return to the question: What is next? To summarize a wider discussion,[41,42] nanochemistry has highlighted the weakness of some chemistry boundaries where distinctions between ''divisions'' of chemistry exist, a nanomaterial has often emerged to bridge the gap. We have materials that are neither clusters nor crystals, we have materials that are neither polymers nor nanowires, we have materials with a synergistic hybrid nature. None of these materials can be understood through a single lens.

Nobody knows what lies ahead in the field, and the issue is more conceptual than technical. The real questions are whether there is an analogous conceptual shift for chemistry ahead of us and how we can place ourselves in the best conditions to grasp it. Is there a possibility that our strong focus on this field might make us stop wondering and questioning what lies behind the bend?

A new revolution might come from predictive dynamic self-assembly — the ability to predict the formation of dynamically self-assembled patterns from arbitrary energy fluxes, building-block characteristics, and boundary conditions — or it could come in the form of error-prone reactions, creating self-replicating chemical structures able to evolve and adapt.

Nanochemistry is especially interesting and exciting for young researchers who are happy to study something different for their undergraduate studies, and it will be a source of myriad discoveries and breakthroughs, for decades to come. But we still do not know how and to what extent it will impact upon the lives of people. One has to now pose hard questions such as: Are we really going to change the way people are diagnosed and cured or the way we produce energy or clean up the environment or the way we communicate? These advances will happen but likely not through nanochemistry or nanoscience alone. In order to let nanochemistry achieve its greater promise in the body of science we should avoid making it a niche. We will then be better positioned to spot earlier the real ''next big thing'' that is lying beyond nano.

***Nano has shuffled the deck and we should keep it shuffled, instead of trying to put the cards back in order.***

This is especially true for young up-and-coming scientists, as there is an opportunity to show them that nanochemistry is not just about making a different nanocrystal, as there is so much more to it than that! One of us recalls about ten years ago, when delivering an introductory lecture to students considering the University of Toronto Nanoengineering program, a student who asked, "Why should I risk my career in a field that might not make it?" The answer to this question was that "we are at the beginning of a global revolution, the field is most likely going to make it" and that "the risk is you *not* being involved." This answer was tempered with the added proviso that, even if the field did not make it, the multidisciplinary training you will receive by being part of the revolution will put you in great stead for any career in science. We believe that is still the answer!

We believe that nanochemistry has shaken the framework of chemistry. It has weakened boundaries that were set in past centuries when chemistry was still an ill-defined science. Nano has shuffled the deck and we should keep it shuffled, instead of trying to put the cards back in order.

This could be seen as a return to our origins, as scientists, when science was not as much seen as a more or less linear summation of arbitrarily defined disciplines but as a way to search for answers and solve problems.


## Acknowledgements

*G.A.O. is Canada Research Chair in Materials Chemistry. The authors are deeply indebted to the NSERC for financial support. We thank George M. Whitesides, Robert Whetten, Younan Xia, Greg Scholes, Josef Breu, Douglas Stefan, Claus Feldmann, Bettina Lotsch, and Dieter Fenske for illuminating discussions.*



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Received: January 20, 2009
Revised: February 25, 2009
Published online: April 29, 2009