From Ideas to Innovation: Nanochemistry as a Case Study

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Just as research on molecules fuelled industries of the 20th Century it is now evident that some major industrial developments of the 21st Century will be founded upon research and development on nanomaterials. In this context, the past 15 years or so have seen an unprecedented push towards innovation within the academic chemistry sector, driven by the vertiginous trend of the hype cycle associated with nanotechnology. Now that the dust is starting to settle, we are in a better position to take a step back and evaluate the after-effects within the academic practice.

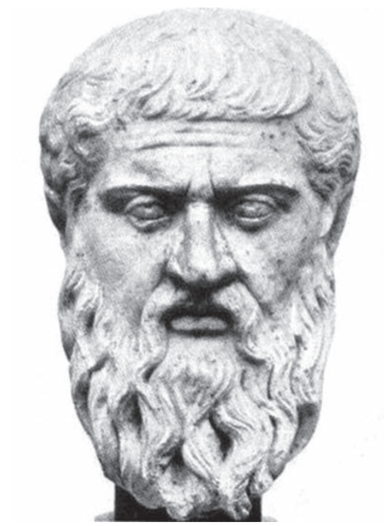

Figure 1. Plato, depicted in this marble bust, wrote on the relation between necessity and invention in his book *The Republic*.

Preamble

In meeting the technological challenges of the future, it is worth recalling the prescient statement of Plato (**Figure 1**) in his book *The Republic*, written in 360 B.C. "Necessity is the mother of invention".[1] While this message is still indisputable to this day, centuries of technological progress have taught us the opposite to be true as well: invention is the mother of necessity—what could be in fact more of a cliché today, as we search for solutions to problems such as sustainable energy, clean air and water, a secure food supply, the management of climate, and enhancing human health and safety. These are problems for which our technology is partly responsible and which we believe we can solve. They are today's grand challenges, 24 centuries after Plato, and chemistry is uniquely equipped to face them.[2]

These global issues present a scientific, philosophical, and sociological challenge to the academic research community. Historically, the role of science has been to generate knowledge. This knowledge led to the Kuhnian paradigm shifts, which changed our views of the world (gravitation, relativity, quantum mechanics) and the way it works (electricity).[3] Nonetheless, with few exceptions, society rarely counted on scientists to turn things around, even at times of war. The Manhattan Project and the Apollo Program, while in a sense more oriented at solving massive engineering problems, were two events that changed the public's perception of science. Suddenly, the scientists were not the "village shamans" anymore, but government workers one could rely on for unexpected solutions and new capabilities. Now, as these global issues unfold, unprecedented expectations towards science and engineering are blended with minimal expectations towards politics, which is widely perceived as being less dependable and surely less trustworthy. As a result, scientists and engineers are expected, somehow, to save the day. Compared to the times of the Manhattan Project and the Apollo Program, the scientific community in general does not seem to perceive the same kind of emergency. We believe that these diverging expectations should be reason for concern.

Another aspect of this challenge relates to comfort zones. Most of us scientists like to understand how things work: the process of reverse engineering Nature's masterful work. And we generally like to do it within the framework of what we know, our own field, our own skill-set, our own community. What is now demanded of us is to directly engineer the solution to complex interdisciplinary problems. Discovery and intellectual curiosity are being pushed into the shadows. This process of constrained problem solving and invention, while

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familiar to scientists in Research & Development, is still uncomfortable to most academic scientists who still feel it to be mostly engineering's turf.

Lastly, globalization and the loss of manufacturing are forcing the developed world's economies to become knowledge-based economies. Academic labs are then expected to transform invention into innovation, and make money, generate jobs, and help keep the nation afloat in a sea of competitors. And they are expected to do this with dwindling funding, uncompetitive salaries, and an all-time low genuine interest towards science from the youngest generations (at least in the western world).

While we can probably afford to proceed with business as usual, there are risks associated with remaining indifferent to the change that is occurring in society and in what society expects and needs from us as a community. Despite the understandable resistance of many academics who see this trend as a vulgarization of the historical role of academia, this is the reality that we are facing. There is no going back, but there can be adoption and adaptation. Our relation with invention and innovation will be at the center of the scientific stage for the coming decades, especially in fields such as nanoscience and nanochemistry, for which additional expectations have been built by the hype cycle.

Nanotechnology, Nanochemistry, and the Hype Cycle

Nanoscience finds itself in a unique situation with respect to the relation between invention and innovation and how they could impact the solution of our global problems. It is a reasonably new field, built on some new scientific insights and discoveries that have changed and are changing the way we look at matter and its interaction with energy, chemicals, and biological systems.[4]

On the one hand, it is safe to assume that the range of new physicochemical capabilities and inventions provided by nanoscience will eventually be crucial for the solution of many global issues. On the other hand, nanoscience has a special relation with innovation. Its technology, nanotechnology, was defined essentially at the same time of its birth on lab benches. This has led to an early triggering of the technological hype cycle, which was probably premature to the science supporting it. This is not something unique to nanoscience, since similar considerations can be made, for example, about spintronics, quantum computation, or genomics. This anticipation of technological expectations has more to do with the amplified expectations towards science in modern society, as previously mentioned, than with the science itself. In the case of nanotechnology, these amplified expectations took a compelling scale driving scientists to i) accelerate their acceptance that scientific research in chemistry and physics could include innovation, ii) become innovators themselves, and too often iii) fuelling the hype in various ways in order to maintain the necessary funding to pursue their innovations.

The hype cycle, as formalized by Gartner in 1995 (see **Figure 2**), describes the temporal evolution of expectations towards a technology. It can be seen as the product of various aspects of modern society: widespread access to information, media sensationalism, democracy, peer-reviewed targeted funding schemes, the academic perception of "fame" and "fortune," and widespread scientific pseudoliteracy. While the sociological and psychological aspects of this recurring phenomenon are obviously beyond this essay, the management of scientific hype cycles is sadly becoming (or it always was?) an essential part of science, as it largely shapes fundamental aspects of our profession, such as funding, recognition, or, quite simply, getting a job at all.

Invention and Nanochemistry

From a scientific perspective, following Schumpeter, an invention is a discovery ripe with technological potential, whereas in technology, innovation is an invention made to work for the benefit of humankind. In business the philosophy is somewhat different. Invention is the conversion of money into ideas whereas innovation is the translation of ideas into money.

In any walk of life, having ideas that nobody has imagined while knowing what everybody knows, is the hallmark of creativity. It is the human way of generating order out of chaos, and it is an exhilarating experience that inspires creative individuals to create. In business creativity is often considered synonymous with innovation. In scientific research, different forms of creativity are associated with different kinds of scientific pursuit. The "problem solving" creativity behind inventiveness is different from the "analytical" creativity, which is harnessed to discover and explain phenomena. One answers the question "how can we solve this problem?" while

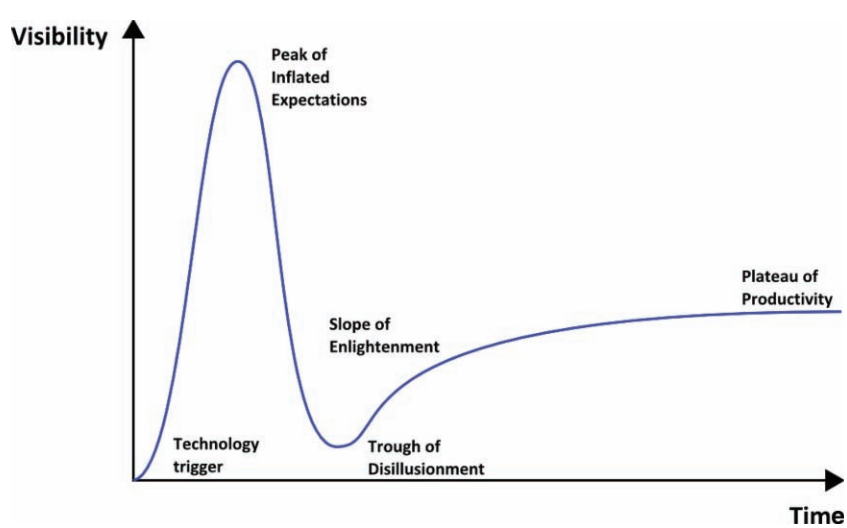

Figure 2. The hype cycle, as proposed by Gartner, Inc. in 1995, identifies the various stages of expectations towards a technology as a function of its stage of development.

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the other answers the question "how does this work?" They both tap on the very same talent of the brain at connecting previously disconnected ideas and verify the logic and consequences of such connections. They differ in their objectives and boundary conditions. Analytical creativity takes the object of one's investigation and finds how to divide it and simplify it into chunks that are manageable, rationally understandable, and experimentally verifiable. Analytical creativity is deconstructive: it identifies connections within the object of investigation that can be severed to make its functioning simpler to understand. Problem solving creativity is instead constructive: it connects things outside of the problem and identifies which of those connections can be the solution to the problem at hand. Oftentimes the connection is identified as a solution for a different or unknown problem. The discovery of the laser was a solution without a problem and look where we are today!

Academic scientists are trained in teaching and research. Invention and its entrepreneurial transformation into innovation are somewhat different processes, based on a different skill set which is not systematically developed by modern science degrees. The traditional belief behind scientific education in academia is that creativity cannot be taught, that imagination is a gift, and that intuition should be controlled and treated with a certain degree of diffidence. It is almost as if the admission of creativity and imagination on the stage of the scientific discourse would demean the nobility of science by contaminating its perceived rationality with the irrationality of creation and imagination. The historical (and continuing) struggle of science to emerge as a force of reason has led, among other things, to the denial of those all-important but irrational aspects of the process of creation and discovery. While many like to cite the quote "Imagination is more important than knowledge", it is generally more due to a romantic fascination for its imaginative author than to a willingness to act on it. Scientific degrees are mostly formulated on the assumption that knowledge, pure and simple, is almost the only thing that we can and should teach. And while we admit that it is not really clear how one should teach creativity, it is proven that many things can be done to encourage it, stimulate it, and empower it. We believe that this "artistic" aspect of science has been repressed for way too long, with the danger of stunting the confidence of us scientists in our ability to do invention. For science to answer the need of bringing ideas to innovation, it is necessary that we change also the way we train the next generation of scientists.

In the field of nanochemistry discovering something entirely new often follows a series of steps familiar to those in materials chemistry, but with the added requirement of having to understand and apply scaling laws, namely how to exploit the way chemical and physical properties of nanoscale materials change with size. And because every nanomaterials property scales with size in a different way the process of invention requires a particular way of thinking about synthesis/structure/property relations compared to the traditional way one applies to bulk materials. Inventive nanochemistry emerges by discovering how these relations can be orchestrated to create functionality and innovative nanochemistry transforms this functionality into technology.

Innovation in Nanochemistry

The nanoscience food chain begins with nanochemistry. To amplify, nanochemistry involves the utilization of a chemical synthesis approach to make new materials with at least one physical dimension straddling the molecular and macroscopic world.[5,6] Can we look forward to "Better Living through Nanochemistry"? This expression is an intentional reminder of the famous slogan used in the 20th Century that molecular chemistry, despite its well-publicized shortcomings, has enormously benefited humankind. In this vein, some of the highest profile nanomaterials to have evoked commercial interest comprise carbon based nanostructures represented by fullerenes, carbon nanotubes, graphenes, and diamond; metal oxide nanostructures exemplified by silicon, titanium, zinc, and iron oxide; semiconductor nanostructures like silicon, indium arsenide, lead, bismuth, and cadmium chalcogenides; metallic nanostructures typified by gold, silver, and platinum-iron alloys; opal-based nanostructures; porous nanostructures exemplified by nanozeolites, nanochannel membranes, metal organic frameworks, periodic mesoporous silicas, organosilicas, and carbons; polymer nanostructures of the block copolymer, polyelectrolyte, dendrimer, liquid crystal and polymer gel variety; and biopolymer nanostructures illustrated by DNA, proteins, peptides, and lipid vesicles. And if this is not enough, composites of these nanomaterials, the synergistic integration of which provides hybrid materials whose performance can transcend that of the component parts.

The act of innovation in science is often driven by the desire to create something that the world has never seen before: something transformative (like the telephone), which creates a new market, or something better (like the cell-phone) than what currently exists, which completely supplants previous technologies (the process of creative destruction described by Sombart and Schumpeter). In the first case the motivation for innovation is in general to solve a problem or generate a capability. In the second case it might be to make something more energy efficient, smaller, faster, longer lasting, greener, safer, or cheaper.

In the context of academic spin-off companies, it is worth mentioning that innovation, or the transfer of an invention into a tangible product that can be sold on the marketplace, have in the main been overlooked by academia, both with respect to research and education. In academia, purely curiosity-driven scientific research inspired by the excitement, satisfaction and beauty of creating new knowledge for the good of humanity has proven to be an excellent training-ground for students to discover whether they are creative, deeply analytical or technically competent but it is not usually an environment in which students are trained to either invent or innovate. This situation is however changing as more professors and their students experience first-hand the entire process of transforming an idea into an invention and ultimately in innovation. Whether the venture is successful or unsuccessful they then serve as role models for the next group of students who want to join the fray. Entrepreneurship courses are beginning to emerge in many universities to educate and train students how to take a laboratory invention into the marketplace. Innovation and technology transfer groups and incubation space are today more commonplace in and around most universities to advise and assist professors and their students on how to create and house a spin-off company, including searching the patent literature, writing and filing of patents, establishing investment opportunities, developing business plans and delving into market research to define the best chance their widget will make it to the consumer to ensure the company will survive by turning a profit. The synergy between the scientific expertise (provided by the scientists) and the business expertise (provided by investors, managers and marketing experts) is crucial to the success of a start-up venture.

In the old model of nurturing wealth creation through innovation, academic scientists would typically transform new ideas, analytical techniques and prototypes into published work in the open literature. Companies would beach comb this literature for new ideas, concepts and methods that can be best suited for their commercialization needs and engineer and optimize technology performance, reproducibility, stability, reliability, scalability, manufacturability and safety of targeted products, processes, and devices.

The new model of the entrepreneurial academic stepping into the innovation arena traditionally reserved for company research and development scientists and engineers, accountants and lawyers, marketing and business managers, introduces a novel element of change into the risk-benefit cycle of discovery and invention, and the job responsibility and skill set required to transition scientific ideas to technologies that work, that create jobs and that help society and the economy.

A perceived and justifiable concern in this context is that academics involved in such commercially driven research ventures will be so caught up in the race to deliver the highest performing nanotechnologies to the marketplace they will miss those disruptive fundamental scientific breakthroughs, planned or serendipitous, that are historically expected by industry and government to emerge from university research laboratories, especially the big advances that change our world and improve the quality of life for humankind.

We do not think we should be too pessimistic. Entrepreneurship in academia does not sponsor explicitly incremental science, but rather the opposite. Companies are more successful when founded on real breakthroughs than on marginal improvements over existing technologies. We can think instead of several situations where the perceived rewards of entrepreneurship might stimulate minds to be more daring, more exploratory, and more creative. Also we can think of many students who could be attracted by the possibility of starting a tech company by studying science, who would otherwise go straight to an MBA degree or other "natural born academics" that might be otherwise drawn away from an academic career due to the poor salaries and now instead can think of using their creativity and love for science to start companies, and making a good living away from the safety, freedom and intellectual stimulation of an academic post. But we can also think of many situations, especially for already successful academic entrepreneurs, where their focus might shift towards optimizing their initial breakthrough in order to "make it happen." These behaviors are not new and they occurred well before we had entrepreneurship in academia. The history of science is replete with examples of scientists that spent decades of their life to work the details of their one, maybe underappreciated, breakthrough, instead of moving on to greater things. What has changed is the type of rewards. Before entrepreneurship, one might have been looking for reward especially in the form of acceptance by the community (the "consensus" that you are right, often wrongly interpreted as meaning that you are indeed right, and that your name will be remembered). Now, those kinds of rewards might become secondary to making a good business which pays the bills, gives good jobs to your beloved students and to other gifted but unemployed scientists, and maybe makes a more visible difference in the real world. And while the rewards might change, the task is still the same and it is that your science needs to be new and needs to be right. Otherwise, in the first case you do not get acceptance, while in the second case your business will not go very far, both outcomes being rather unpleasant, even when interpreted in the sense that everybody else is wrong.

If we are to be constructive and not revisionists, we should say that the purpose of a local government and of a university, in the interest of maximizing the impact of its research and the enthusiasm of its students, should then be to provide sufficient incentives and support to successful entrepreneurial academics so that they will feel comfortable with being less involved with the business they have created and with working on new research and breakthroughs that will either enhance the business or create new start-ups.

In terms of education, the concerns over entrepreneurship are more serious. The fear is that academics involved in entrepreneurship might in some cases prioritize their nascent business over the interests and needs of their students. This is a very delicate subject since no academic wants to be regulated on how he spends his own time or prioritizes his work. But at the same time, all students need to be safeguarded especially if we want them to have any wish to become the next generation of academics. One argument could be that the system would self-regulate as the reputation of academics spreads very rapidly and, for better or for worse, is widely publicized in student forums on the internet. One can then expect that the best students, the ones that have multiple options on where to go for doctoral or post-doctoral research, will consider this information before making a choice, thus promoting virtuous behavior in professors. This is a valid argument but self-regulation still does not protect the students that either do not have access to information on the reputation of specific professors, or that work for a professor who has not yet developed a reputation. We believe that regulation is better avoided and that problematic situations should be monitored and dealt with within each department on a case by case basis, while allowing each student to feel protected about expressing concerns.

Nanochemistry Spin-Off Case Histories

In concluding this Essay we have decided to look at some new companies listed on the Internet from a smorgasbord of hundreds whose technology portfolios are based on nanochemistry breakthroughs. The objective in what follows is to illustrate some case histories on how nanochemistry in the areas such as soft lithography, nanowires, nanocrystals, opals, mesoporous materials, nanostructured block copolymers, and nanomedicine, is now being actively developed into commercialized products. We believe this is an appealing way to finally connect nanochemistry ideas to innovation, the subject of this essay. Note that the information presented below has in some parts been obtained from the company's website and might thus be already obsolete.

Batteries

A123 Systems is a start up founded in 2001 and is based on the invention of nanostructured lithium metal phosphate cathodes by Yet-Ming Chiang's group at MIT. The first product came out in 2005 and was used to power cordless power tools from Black and Decker. The company has now 2000 employees and is aiming especially at the transportation market. The company has raised a total of 350 million US$ from private investors and was awarded a 249 million US$ grant from the Department of Energy of the USA for manufacturing.

Seeo Incorporated, founded in 2007 on the basis of intellectual property developed at the Lawrence Berkeley National Labs, is tackling the issue of lithium batteries by using block copolymer electrolytes, which could enable entirely solid state batteries, avoiding the use of volatile or flammable components.

Wiring

In an age of increasing fuel cost and greater attention to fuel efficiency, the reduction of weight in vehicles is essential. One aspect is to reduce the weight of the electrical wiring. For example Nanocomp Technologies, founded in 2004 is aiming at commercializing the invention of carbon nanotubes by replacing copper wires with these carbon nanostructures, reducing the weight of cables by 30–70%. The processes they have developed allow them to manufacture yarns and sheets of carbon nanotubes on a large scale.

Solar Cells

Dyesol Incorporated is an Australian startup company founded in 2004 with the intent to commercialize the invention of dye-sensitized solar cell (DSSC) by Michael Grätzel's group at EPFL. This company now sells equipment, materials, and components for DSSC. These products have been implemented in glass facades of commercial buildings and in portable small-scale applications.

Light-Emitting Diodes (LEDs)

Nanosys Incorporated is a start-up founded in 2001 by nanoscience pioneers Charles Lieber, Peidong Yang, Jim Heath, Paul Alivisatos and Moungi Bawendi and is based on some substantial intellectual property (~700 patents). The current aim of the company is to use nanomaterials primarily for LED and lithium ion batteries. In the case of LED, Nanosys has established an agreement with LG Innotek for the first commercial application of quantum dots in consumer electronics, promising a much enhanced performance when compared to competing technologies.

Golf Clubs

Integran Technologies Incorporated is developing metallurgical nanotechnologies for structural components. Its achievements go from the first large-scale structural application of nanostructured materials in nuclear steam generator repair, and one of the earliest issued US patents in the field of nanotechnology, to next generation golf clubs and baseball bats.

Bioanalysis

Nanosphere Incorporated is a startup founded in 2000 on the basis of the intellectual property developed at Northwestern University by Chad Mirkin's group. Their technology is based on the invention of ultrasensitive detection of nucleic acids and proteins by functionalized gold nanoparticles. The detection is accomplished with a device called Verigene which is now sold worldwide.

MolecularStamping is a startup founded in 2006 which commercialized DNA microarrays produced by supramolecular nanostamping. Their main product, aimed for nosocomial infections, is designed to identify sepsis-inducing pathogens in blood without the need of polymerase chain reaction (PCR).

Conclusion

The relationship between the academic scientific community and the world is changing at a rate which is unprecedented in history. This transformation is based on three concurrent trends: i) problems of inherently chemical nature rapidly becoming the most important issues facing the planet,[2] ii) the burgeoning expectations of the masses towards science, together with decreasing expectations towards politics and religion, iii) a shifting global economy where established countries have largely lost their manufacturing primacy and can now only compete by out-innovating the rest of the world.

The scientific community is facing a time of unprecedented power, responsibility, and accountability. This transformation will inevitably require or induce a change in the way we run academic research and teach science. Our only choice is between managing this change or being subjected to it.

In this Essay we have argued on how invention and innovation will be the end points of this change. It is up to us as the academic community to make sure that, **while reaching**

for the highest standards of scientific methodology, we invent stuff that **really works**, that **really solves or addresses** a problem that **really matters**, and then boldly go and innovate with it with no fear or prudence. We believe that this change, if managed correctly, will not suppress fundamental research, but might instead strengthen the most revolutionary, disruptive, and original components of it: the so-called "black swans." There is nothing that drives invention and innovation as one **really new** discovery.

Has nanochemistry provided discoveries that really work and really address the problems that matter today? We believe it is too early to say. As we progress forward in the hype cycle, we are bound to enter a productive phase, where the new discoveries and materials of nanoscience will be tested against the existing state of the art.

In any case, nanochemistry and nanoscience are uniquely placed to be flag-bearers for the change that is coming. The hype surrounding these fields might eventually turn out to be not completely detrimental. It will force the flag up high and will point it towards invention and innovation.

Acknowledgements

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