I am taking the opportunity of this invited article to share some personal thoughts about the way academic science education has developed during my life. It seems clear that, if the thrust that allowed our scientific world to bloom stems from humanity's insatiable thirst for knowledge and art, the means allocated by society to materialize it, as we know it, are more deeply intertwined with the market and economy than I had previously thought. Paradigms that shaped our academic world have changed gradually, hence almost imperceptibly, but not necessarily in the interest of the future of science.
*[**Ed. Note**: The opinions expressed in this article are those of the author and not* Interface *nor The Electrochemical Society.* Interface *welcomes feedback on this article.]*

The Red Queen and the Russian Dolls

by Christian Amatore

As far as I can remember, I have always been interested in understanding the whys of what I was observing—the mysteries with which I have been confronted. I was constantly interrogating my parents to get explanations. Today, I know that some of the questions I asked were, in fact, scientific ones: "Why can clouds flying in the sky suddenly *decide* to burst open and release rain?" "How can huge sand dunes[1] travel over half a mile during a single night while keeping the same shape?" While others were just puerile thoughts, I felt just as concerned with knowing the answers.

I was the first son of an immigrant family from Sicily, and the first French-born in my family. My parents were caring and, as I could discern only later, not financially wealthy, but incredibly rich in terms of the care they provided. They always tried to answer my questions. The trivial ones were easy for them, but the more serious ones were challenging. Indeed, even though both of them were extremely smart, they had to stop school after completing the elementary level. They always did their best to provide me with a logical answer, either using rational arguments, or most often, by relying on experimental analogies. When they could not answer, they never evaded my questions. Instead, they said, "You are right to ask this question, but we don't know the answer. It's even possible that, so far, nobody knows the answer." They never replied, "You are too young to understand," which is the best way to discourage kids from trying to find meaning in their surrounding world.

I learned later that their answers, though adequate for me at the time and logically correct, were often wrong, simply because they did not have the chance to learn the natural laws that my questions involved. Conversely, their experimental analogies and models were generally correct and captured, at least in part, the essence of the real phenomena that I wanted to understand.

I did not know back then, however, that my parents' attitude had been essential in starting me on the path toward science. Not only did they encourage my *pleasure of finding things out*,[2] but they taught me that there is no shame in admitting that one does not know. They also helped me recognize that some of my questions deserved a rational answer, while others were puerile fantasies. It is enough to consult the internet or YouTube to realize that most of our citizens today cannot so clearly discriminate between rational and correct information, and unfounded and eccentric *alternative facts*.

Even if it was fully beyond my awareness, my parents' use of experimental models to address questions taught me one of the important qualities and great powers of science. Indeed, from teaching purposes to creative research, scientists constantly rely on the exceptional ability of the human mind to distill the important features of one complex phenomenon and cast them into a real or imaginary[3] contraption (a model). These features can then be transposed back into the initial phenomenon to better understand its causes or nature.[4] Art and this primeval desire to interrogate nature in order to rationalize it are, in my view, two distinctive traits of humanity. Lay people, like my parents, often unknowingly proceed along the same lines, but are generally stalled at the level of intuitive conclusions, lacking the scientific and mathematical skills to progress further.

In truth, the modern scientific era did not only pass to us its thirst for scientific understanding; far more importantly, it gave us methods to satiate this thirst with rigor. We are supposed to be introduced to these methods in school, under the guidance of teachers and professors. This was precisely the role of school in my time. Teachers and professors did not try

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to imprint facts in our memories without anchoring them to the explanations that our brains required;[5] these explanations often had to be oversimplified, but they conveyed general sense and reasoning without significant distortion. For example, in elementary school, we had books on *leçons de choses* (i.e., lessons about natural things). Each lesson was built like a Sherlock Holmes novel, starting with a somewhat mysterious story, assembling a patchwork of seemingly unrelated observations, and progressively solving the puzzle with the aid of proper hints, up until the point when a single logical conclusion could be reached. From each lesson we derived a *bring home message*, which summarized the scientific point or points that we had just come to understand. Retrospectively, I think these *leçons de choses* provided a better introduction to science and creative scientific research than one can find in most schoolbooks today, and even in most college textbooks.

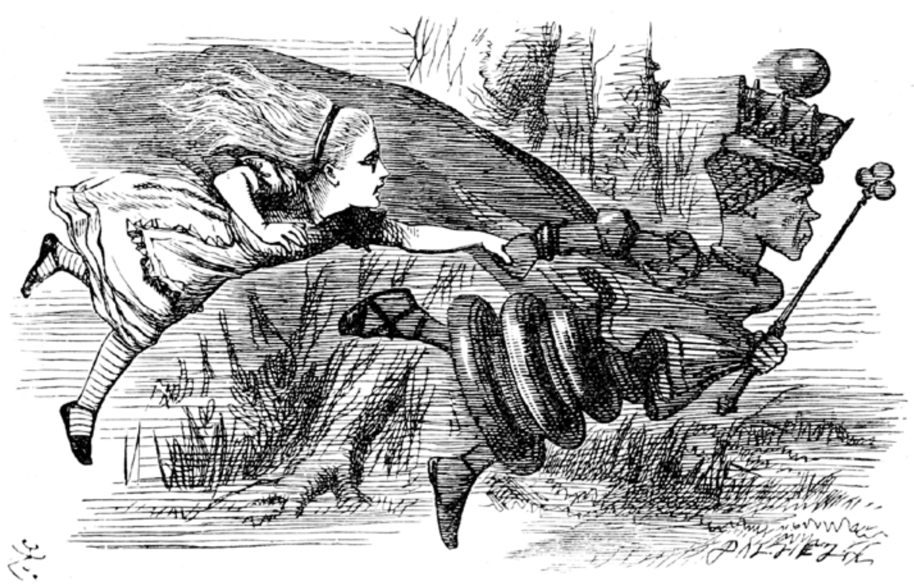

Illustration by John Tenniel of Alice and the Red Queen running to keep in place, from Lewis Carroll's Through the Looking Glass.

Along with these *leçons de choses*, our schoolbooks offered passages from reputed French writers, and texts relating the feats and life episodes of famous and impressive persons. They were not only telling us their achievements, but also casting these figures amid the doubts and struggles they experienced while they worked to change the world. I can see, in retrospect, that these lectures demonstrated that explorers of science were no different from Columbus, Marco Polo, or Livingstone. All of them were people who lived within their epochs, but were exploring new worlds, expecting to bring back nuggets that they imagined would contribute to our welfare. The only difference was that the explorers of Earth, like their contemporaries, generally knew what these nuggets were before their journeys began. Explorers of science obeyed their devouring passions and often needed to persuade their contemporaries about the importance and reality of their nuggets. Think about Pasteur and microbes, or Marie Curie and radioactivity. Furthermore, we could easily understand that their creative longing never stopped during their lives: finding out one thing would simply expose another one whose existence was unsuspected up until the previous enigma was solved. In other words, this was telling us that creative science is like art. Both proceed like an infinite series of Russian dolls: no one can predict if a new doll will be discovered inside before the outer doll is cracked open.[6]

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One is even more baffled when trying to predict any industrial application of newly exposed knowledge.[7] This is where academic research differs from engineering. The usual distinction between fundamental and applied research is clearly wrong, since there is as much applied research in the so-called fundamentals as there is fundamental research in the applied. The real distinction is between open research (the never-ending Russian dolls) and research finalized toward an already identified and selected target.[8]

Until now, I have used my own experiences to report on how these initial years of my life bred boundaries that set me on the path that guided me toward academic science. Indeed, my trajectory naturally progressed along this path and led me to start a thesis under the attentive guidance of Jean-Michel Savéant and during a postdoctoral stay with the late Jay K. Kochi. These times marked my beginnings in the world of Russian dolls, to whose spirit I have remained faithful. I believe these experiences, from elementary school to my undergraduate years, were not singular among my age group, except maybe for the good fortune of having parents such as mine and the luck of being taught by many good teachers and professors. Actually, unbeknownst to me at the time, I belong to one of the very few generations to which our societies decided to entrust the pursuit of their future. Indeed, my age group grew during the thirty glorious years (the years following the rapid reconstruction of Europe and Japan after World War II) that led to an almost exponential economic growth in developed countries. On the other hand, on each side of the Iron Curtain, our societies were involved in the Cold War. These factors stimulated open scientific research and technology. Indeed, competition among national economics and prestige, political displays of the value of opposing economic and social systems, and trying to keep the lead in the race for new weapons[9] could not proceed without more and more scientists and engineers involved on each side.

Detecting the best seed scientists in any nook of a country and training them to ensure that, whatever their social origin, they would be able to fully reveal their talents, was a duty of school and a mission assigned to schoolteachers and professors. This has been going on in almost all developed countries for the same reasons. Today, one prefers to euphemistically cover this crude reality under more noble veils. Speaking about the promotion of egalitarian education and social elevators has become the usual and politically correct way to describe this mechanism. However, this is no more correct than speaking about installing social elevators during the Industrial Revolution, which dragged people from the countryside to the cities to serve the machines.[10] The only difference is that, then, in most countries, the middle and upper classes were numerous enough to easily provide the required numbers of scientists and engineers, who were so essential in contributing to the increasing success of the Industrial Revolution. A few exceptions have existed, for sure, but they were generally due to improbable happenstances, like that of Humphry Davy being impressed by the crisp intelligence of the young Michael Faraday. Huge amounts of money were injected into education with the expectation that the returns would exceed the initial cost and lead to future commercial and political dominance. This worked beyond most optimistic expectations, generating a near exponential growth of economies.

As any realistic economist should have predicted, this economic rise was bound to meet a plateau. The first evidence of this materialized in the middle of the 1970s when the first oil crisis struck the whole Occidental world. This rapidly amplified when Japan, and then Korea, entered with remarkable dynamism into the science- and high technology-based world economy, accompanied by China, and with India joining the process. The problem is not at all with the globalization of the economy, but rather with the fact that this somewhat broke down the dream-cash machine that had been continuously powering the development of the science- and technology-based growth of traditional Occidental economies.[11] Indeed, this growth could happen only because lay people believed that it would work. They were spontaneously willing to provide the money required to make it work. In this respect, it is important to recognize that this input was much larger than what any government could inject using taxes.[12] While this faith was progressively disintegrating, the number of scientists was reaching unprecedented records, having grown continuously during the heyday of economic expansion to contribute to either the growth of companies or academia.

Evidently, the conjunction between a less efficient dream-cash machine and a large number of scientists necessarily decreased the mean research funds per capita. In an attempt to derail this process and re-attract private investments, the public agencies of many countries decided that access to government funds required justifying short-term financial returns. The imbecility of such politically correct directives is all the more evident when one notices that the technology-based wealth of our societies is deeply-rooted in unpredicted outcomes of previous open research performed by curiosity-driven scientists who thought and acted in their own ways, following their educated guesses. The outcome of open research cannot be predicted—and certainly cannot be directed—based on short-term returns. Rules governing finalized research simply do not apply to open research. By definition, most open research cannot boast predictable short-term applications with which to justify access to taxpayers' money. For example, if we did not know now that it would lead to transistors and computer chips, or Moore's law on the growth of electronics, what governmental or private agency would fund today a research project on the purification of silicon, and then on methods precisely designed to mess up with such extra pure silicon? Who would support any research today on packet-switched networks as it started at CERN before becoming the internet, which would become so central to the development of new forms of economy? Or, closer to our field, and on more modest grounds, would Bard's or Savéant's research on the 32 different mechanisms of electro-hydrodimerization be appealing to agencies nowadays?

"Today almost all academic researchers have to compete on priority targets generally imposed from above."

This situation resulted in focusing funding on what seemed appealing. Unfortunately, today almost all academic researchers have to compete on priority targets generally imposed from above, and often based on short-term oriented fancies. Forced into participation, we have no choice but to embark, like Alice, in a sort of Red Queen's race, having to run fast constantly only to remain in the same spot.[13]

Fortunately, the private dream-cash machine shows visible signs of recovery, stimulated by the vision and impulses of billionaires, and based on models tested in Silicon Valley. For example, space conquest seems to be leaving the public domain to become a reality in the hands of entrepreneurs like the founder of Tesla Motors, and is attracting huge resources from giants like Google, followed by venture capital. Regrettably, at the same time, the main preoccupation of scientific universities and institutions seems to be improving their rankings in the Shanghai or Times classifications, suggesting that they strongly prioritize high educational aspects as opposed to research. Clearly, the Red Queen's race does not seem to be ending soon in the academic scientific world.

To drive the nail deeper, most scientific publishers have entered into a strong competitive struggle driven mostly by financial interest. To win their own Red Queen's race, they need to compete in attracting, as before, the best papers from the best authors. Unfortunately, *best* no longer has the same meaning as it had during the Russian dolls' heyday. Now, *best* is measured in terms of journal impact factors (JIFs) and h-indexes. However, the very definition of JIFs[14] dictates that research that can be rapidly cited, possibly by public media, is most welcome.[15] It is evident that most of the fully seminal research cannot contribute to good JIFs. Indeed, even if reading such a paper would stimulate many academic scientists to immediately follow suit, the timescale needed for obtaining the grant required to perform their own research in this new direction, carry it out, and get it published generally exceeds the two year gap duration imposed by the JIF. Hence, publication of fully unexpected results is no longer the most favored by JIF-driven journals.[16]

"Most scientific publishers have entered into a strong competitive struggle driven mostly by financial interest."

Such business-driven concurrence among scientific journals can only increase the Red Queen's speed in her race and lead to the complete extinction of the Russian dolls research model. Is this what we really want? Will it be beneficial to our society? ■

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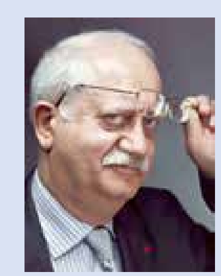
About the Author



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Notes

1. At the time my family was living in Laghouat, a city located in Algeria (at the time, Algeria was not a colony; it was part of France as Corsica is today) at the north border of the Sahara—hence my concern with moving sand dunes rather than with *stable* hills or mountains, which I discovered only later in my life.
2. I could not resist in borrowing this marvelous expression from Richard Feynman's eponymous book title.
3. So-called thought experiments are usually attributed to Einstein. Yet, if it is true that Einstein often used this argumentative method, he did not invent it. In fact, this existed even before Euclidean mathematics, being named *δεικνυμι* (i.e., "I show") in ancient Greek. To the best of my knowledge, this was the most ancient method of establishing a proof—or of disproving a previous rationale through providing a paradox, as Einstein loved to do—by casting emphasis on a purely conceptual argument rather than on an experimental contrivance.
4. For example, we have all been taught that Galileo was deeply concerned with the role of the sun in the solar system, but we are also taught that he spent huge amounts of time in understanding the laws governing pendulum oscillations. For a long time, I did not understood how he could put aside his insatiable desire to prove that Copernicus was right to find time to investigate some comparatively inconsequential problem. If I had been smarter, I would have understood that Galileo had remarked that the projection of a mobile object circulating along a circular trajectory on one of its diameters corresponds to a linear oscillation (i.e., precisely the sinusoidal movement displayed by a pendulum at short angles). Galileo was not gifted in mathematics, so designing an experimental model was his approach to the problem. Reducing the mechanics of Earth travelling around the sun down to a pendulum oscillating on his desk is, in my view, incredible proof of his genius and profound prescience of how science would construct itself and proceed after him.
5. At least it was like that in France, with most of the teachers and professors who educated my classmates and me. They were adamant, whether in natural sciences or the French language, about teaching us methods to aid in understanding. In some respects, I can now appreciate that for them, *knowing*—though necessary—was somewhat subordinate to *understanding*. They knew that what is memorized generally evaporates quickly, unless it is deeply anchored in clear, logical roots. Wise sub-Saharan African and Chinese adages from time immemorial perfectly illustrate this view (e.g., in modern English, "Give a man a fish, and you feed him for a day; teach a man to fish, and you feed him for a lifetime"). It is disheartening to see how this stands in such contrast with teaching principles enforced in most schools of Occidental countries since the 1980s. Moreover, notwithstanding the known failure of these methods in the U.S., they have been readily spreading to Europe (except for Finland, which has reverted to the previous ones). Does this mean that the past *panem et circenses* strategy is resurfacing as the way of governing nations?
6. For example, compare to Picasso elaborating his quintessence of a bull through exploring so many avenues, often returning back to an abandoned train of thought to pursue it in a different direction. I chose Picasso and his bulls series because he archived all his paintings and drawings, thus providing a prodigious documentation that is often freely accessible. However, this process is common to most creators in art or science. Consider, for example, this quote by Faraday: "I am no poet, but if you think for yourselves, as I proceed, the facts will form a poem in your minds" (cited by Bence Jones in *The Life and Letters of Faraday* (1870), Vol. 2, p. 403).
7. I cannot resist quoting the famous Faraday answer to William Gladstone, then British Chancellor of the Exchequer, who had been so impressed to observe that a field getting out of a magnet bar was strong enough to organize iron fillings into a clear pattern, though one could not feel it or smell it with the human senses. The prime minister asked Faraday what application this prodigious discovery will bring. Faraday answered, "Today, I really cannot foresee any practical value of electricity, but, sir, I am sure that one day you will tax it." This was only 30 years before the invention of the first alternators and electrical engines. Today, except for photovoltaic conversion, all electricity consumed on Earth is produced by Faraday's alternators.
8. Consider, for example, the Wright Brothers or Gustave Eiffel as opposed to Thomas Edison or Steve Jobs. The first two made fundamental scientific discoveries that began important progress, while the second two found a market for applications based on improved, but already existing knowledge.
9. Remember how Sputnik's beeps generated a wave of panic in the U.S. government during the fall of 1957? This led to the expeditious creation of DARPA out of scratch, over the course of just four months, to avoid any future technological or scientific surprises by expanding the frontiers of science and technology through collaboration between academics, industries, and U.S. government partners.
10. Note that, except in France where this was a consequence of the installation of full democracy, the decision to develop schools on a large scale also correlates with the rise of Industrial Revolution. Indeed, a farmhand could gain all required knowledge and practice from his or her parents or neighbors and did not need many writing and calculating skills. Conversely, a factory worker needed such skills to run the machines he or she operated.
11. Spreading global wealth across all nations would certainly benefit humanity as a whole, if traditional market views adapt to this novel norm. In this respect, we have to hope that sub-Saharan Africa will soon join this movement.
12. Though I concentrate here on scientific and technological developments, the same occurred already at the time of the great expeditions across the world to corroborate trade routes for spice and silk. Then, chartered companies such as the Dutch East India Company or the eponymous British ones were literally selling dreams in the form of bonds, whose value was paid back with high interest through the return of a few ships loaded with spices and other high-priced merchandise. Faith in the system and a sufficient percentage of success was enough to generate an accelerated growth. Our recent scientific and technological developments have been more or less powered by the same faith in rising economics. Literally speaking, Sony was telling an exact truth with the slogan "You Dreamed of It, Sony Did It," except that the two *its* referred to two different things.
13. To Alice, who wondered why they had to constantly be running, the Red Queen answered, "Here, you see, it takes all the running you can do, to keep in the same place. If you want to get somewhere else, you must run at least twice as fast as that!" (Lewis Carroll's *Through the Looking-Glass*).
14. The JIF of a journal is the number of citations received in one year by articles published in that journal during the two preceding years, divided by the total number of articles it published during same the two preceding years. Hence, publishing novel papers that are not expected to bring many citations during the next two years lowers a JIF, even if this paper may open a blooming field a few years after. Note that my own h-index and mean citation rate demonstrate that I am not accusing these circumstances for selfish reasons like Aesop's famous fox. Yet, though this is not evident from glancing rapidly at Web of Science or Google Scholar statistics, most of my seminal works, the very ones that contributed to building my scientific reputation, received almost no citations for several years after their publication (i.e., before many others implemented them). A good example is given by microelectrodes, a field which I pioneered with Mark Wightman (Pons and Fleischmann were doing the same on their side), but could not bloom until the National Science Foundation decided to stimulate grant proposals on this topic.
15. This is perfectly obvious with top journals, for which the decision to send a submission to review or reject it without any reviewing is made based on quick assessment of the contribution's potential for boosting the journal's JIFs and stimulating the interest of public media. We have reached a point where catchphrases and the *brittleness* of a title are more valuable than the paper's content.
16. A good example is afforded by Binnig and Rohrer's seminal discovery, which was published in 1982 in *Helvetica Physica Acta* (whose mean JIF was approximately 0.5 from 1992 to 2001), but was soon awarded the 1986 Nobel Prize for the invention of the scanning tunneling microscope. See: G. Binnig and H. Rohrer, *Helv. Phys. Acta*, **55**, 726, (1982).