Genesis of Creativity

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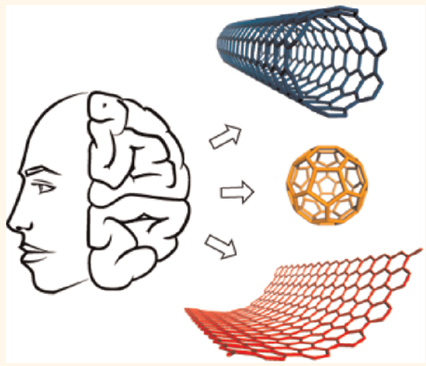
ABSTRACT As advances in nanoscience and nanotechnology are sought, what will be the source of the inspiration to open the doors for new developments? In my opinion, it most often resides in the ingenuity of students, and among those ingenious students, was there a formative spark or a progressive set of stimuli in their childhoods that gave rise to the most precious asset in scientific advance, namely, creativity? Here, I outline the work of three of my students who have propelled the field of nanotechnology, and then I glimpse into their childhood years to see if there lays the key.



On this occasion marking my receipt of the inaugural ACS Nano Lectureship Award for the Americas, for which I am sincerely grateful, I am delighted to write this Perspective. And since this Perspective comes under the banner of the award, rather than focusing upon a specific research area, I will discuss one of my favorite scientific musings: what is the source of a good research idea? For example, the best compliment for a scientist to give or to receive is: "I wish I had thought of that!" But what is the genesis of creativity? Certainly there can be debate as to what is truly creative and whether creativity is even recognizable in the decade or generation of its origin, but I will not address that point. Many would concede that there are clever ideas that manifest themselves in publications that most impress us and where we marvel as we read. And how were the ideas for those scientific contributions birthed? That is what I will discuss from the area that I know best—nanoresearch in my own laboratory and the occasions and the people from which these contributions came. They most often did *not* come from me. What was it that stimulated the thought, the process to the conclusion, and the culmination of the publication? This is not to be a well-researched article discussing the broad findings of sociologists and philosophers of science, but merely reflective thought coming from personal observations of scores of students, postdoctoral associates, and academic colleagues who have shared a part of my own career in the world of nano over the past 25 years.

Wally Scrivens—A Mind of Enormous Creativity. There are some people that have an amazingly creative eye, and Wally Scrivens is a champion among them. Wally joined my research group as a graduate student in 1990. He was enamored by C_{60}, a compound that held little interest for me. But Wally was clearly different, having a curiosity and talent in exploration that was a delight to behold, so I yielded the reigns as he progressed. Wally came to me one day showing me how he could make gram quantities of C_{60} in a round-bottomed flask, using an arc welder and some rods of graphite, and that he could purify C_{60} by the gram just by using activated charcoal (Figure 1).[1−4] Knowing that researchers were struggling to acquire milligrams of pure C_{60} at that time, and they were paying the equivalent of $5000 per gram for it, I too became interested in C_{60}. When we submitted the C_{60} purification manuscript to the *Journal of the American Chemical Society* for review, I got a call from the Editor-in-Chief's student saying that he was trying our purification process according to our prescription—for me that was wonderfully flattering and it highlighted the intense interest in the procedure. Wally was a machine of creative thought that did not end there; for example, he synthesized ^{14}C-labeled C_{60} to track its biodistribution.[5] Sure, Wally had some ideas that failed, but they

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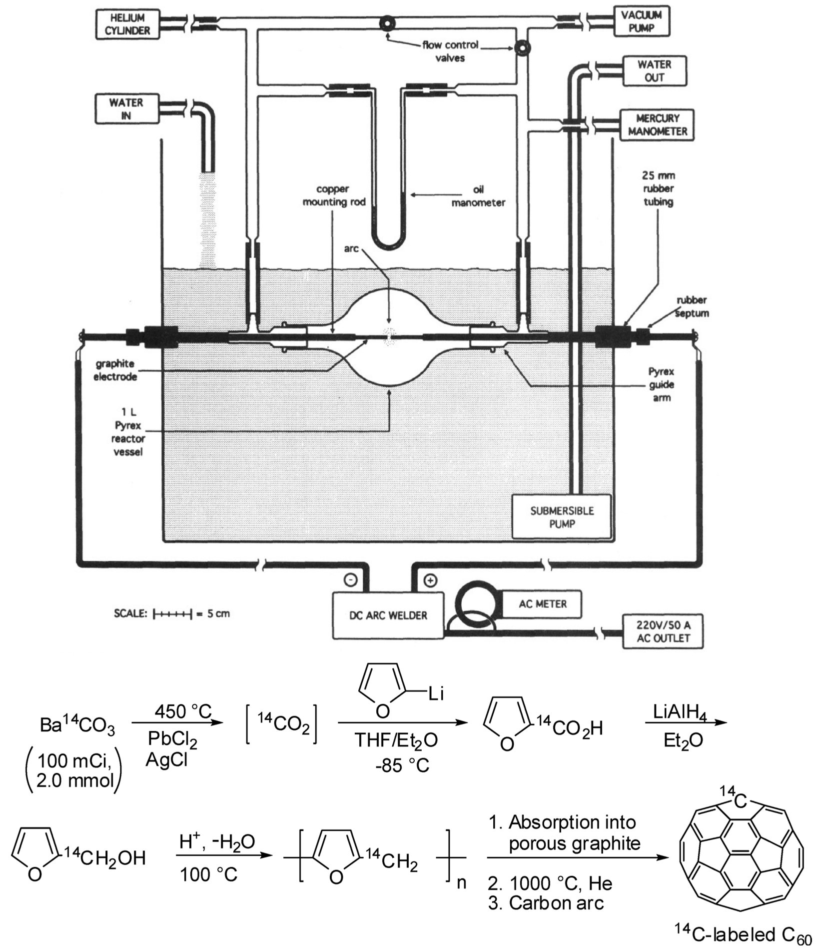

Figure 1. (Top) Round-bottomed flask based method for the preparation of C_{60} and some other higher fullerenes that also led to the simple column chromatography separation of gram quantities of C_{60} and C_{70} using activated charcoal and derivatized polystyrene as stationary phases, respectively. Reproduced from ref 2. Copyright 1992 American Chemical Society. (Bottom) Synthetic scheme shows Wally's route to ^{14}C-labeled C_{60} that was used for *in vivo* and *in vitro* toxicity studies.[1−5]

were a pleasure nonetheless, such as the day we packed 0.308 hollow-point bullets with C_{60} and fired them into the face of a steel anvil in an attempt to make diamond, or his effort to grow ultralong carbon nanotubes by placing a 100000 V source orthogonal to the carbon arc in a round-bottomed flask. What an enjoyable career it is in academic research in nanoscience, where we have the freedom to explore wherever our minds will take us.

Creativity Needs a Helping Hand. What could Wally not do well? He could not pull together his lab reports well. He could not structure his research papers well. He needed supervision in areas where others seemed to do just fine. I was once on a corporate Board of Directors with Michael Nesmith, the base guitar player from the 1960s made-for-TV rock group, "The Monkees". Michael had been successful in several endeavors in media and entertainment, including being the initial developer of MTV. I asked Michael how he had been able to get musicians to work for him without becoming overly frustrated by their idiosyncrasies. His reply was insightful: "You need to expect from talented people what they can deliver, and don't expect from them what they can't deliver." Hence, some assistance for the most creative might be in order as they bless the world with their inventive minds. If I had expected from Wally what I expected from other students in terms of neat and timely delivery of weekly reports, I am not sure that he would have made it through the system. Some will argue that all need the same treatment in these most basic of skills. I agree, in general, but there are special ones that need some special treatment, and the world is all the richer as a result.

The Husbands and the Molecular Computer. In 2000, we were endeavoring to build a molecular computer for delivery to the Defense Advanced Research Projects Agency's Moletronics program. For us, that was a disordered array of molecules in an unknown order of attachment, but where we could provide voltage pulses from the exterior edges and thereby cause the system of molecules to set into desired states, for example, as an AND gate, an OR gate, or a NOR gate, merely by applying the voltage inputs (Figure 2). This project needed a mathematician since the system was

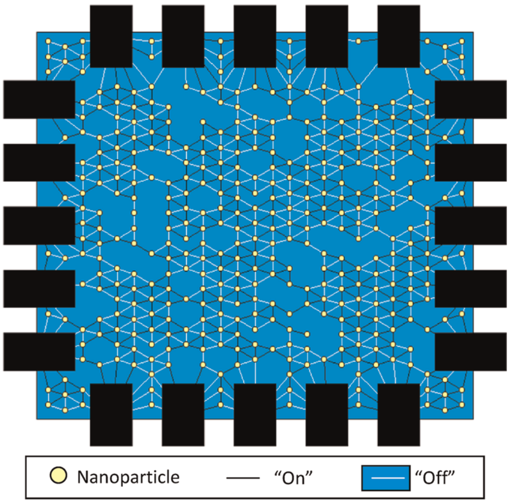

Figure 2. Simulated self-assembled nanocell. The black rectangles at the edges are the input/output leads, the yellow dots are metallic nanoparticles, and the internal lines are molecules that have been set in "On" or "Off" states.[7] Reproduced with permission from ref 7. Copyright 2002 IEEE.

modeled as a series of nonlinear differential equations, which some of my colleagues in the Computer Science Department at Rice had said would not be solvable. At the same time, I learned of a young couple, Chris and Summer Husband, who would be leaving Rice with their Master's degrees in Computer and Applied Mathematics since they were not excited by the research projects being proposed to them for their PhDs, and Chris was already entertaining an offer from Evans and Sutherland, the computer graphics company. I inquired with their professors and the Husbands had high recommendations. So, I went to Chris and Summer's home and I begged them to work for me. I described the project and its implications with all the salesmanship that I could muster, though I did not tell them that the professors in Computer Science had said that the system was unsolvable. The Husbands joined my group for their PhDs. Chris was extraordinary. He could unravel a board-game puzzle in seconds when it took others an hour. In about two years, Chris wrote a program that could solve the molecular computer problem— completely amazing! But Chris's difficulty was that he could not describe the solution well, he could not write the paper well, and he could not debug the program efficiently.[6−8] But his wife, Summer, was excellent at all of those other tasks. As a couple, Chris and Summer were like trained assassins—absolutely unstoppable and frighteningly good as a team. As Michael Nesmith had instructed, I had to expect from Chris what he could deliver: the solution. And Summer could gather the nuggets of gold that came out, debug the programs, and package the work into a publication that could benefit the community for decades. Creativity needs helping hands, and without them, the creative effort does not survive to see the light of day.

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Dmitry Kosynkin—A Master in the Laboratory. Dmitry Kosynkin was a postdoc in my lab, twice. The first time was in 2001. Dmitry was well-trained in Russia, and he had gotten his PhD in organometallic chemistry in the United States. When I hired him, he had been selling overpriced life insurance coupled to annuities. His attitude was a bit gruff, but I felt that I could work with him because his synthetic talent seemed quite good. He did well and propelled the project at hand—synthesizing a series of aryl diazonium salts for functionalization of hydrogen-passivated silicon and carbon nanotubes.[9,10] After two years, he went off for a job, and then left that job to try his hand at making a small fortune exporting used Lexus cars to the bourgeoning Russian market. In 2008, after hearing about Dmitry's dissatisfaction with the exporting business, I was glad to offer him another postdoctoral position in my laboratory because I needed a good pair of synthetic hands for our nanomaterials and nanomedicine projects, and he needed an entry back into chemistry. As soon as Dmitry stepped back into the lab, he became a resource of information to the graduate students. And not long after that, he discovered the potassium permanganate oxidative unzipping of carbon nanotubes to make graphene oxide nanoribbons,[11,12] and then he discovered the potassium metal reductive splitting of carbon nanotubes to make graphene nanoribbons (Figure 3),[13] followed by the high-yielding synthesis of graphene oxide,[14] then the oxidation of carbon black nanoparticles with subsequent covalent functionalization that became the base materials for our nanoreporter project for downhole oil detection,[15] then the use of graphene oxide in oil-well drilling fluids,[16] and on and on. I think that Dmitry only worked 20−30 h per week in the lab, but it was a bargain. At the same time, Dmitry had a painful time (for him and for me) delivering his weekly progress reports, and he was unable to gather all the details needed for publications. By assigning graduate students to follow along with Dmitry, the students could complete the data sets needed, learn techniques from the master, and be co-authors on foundational publications. The student contributions were essential for further developments;[17] without them, the work would not have been publishable. Though Dmitry is now gone from the group, his legacy will be

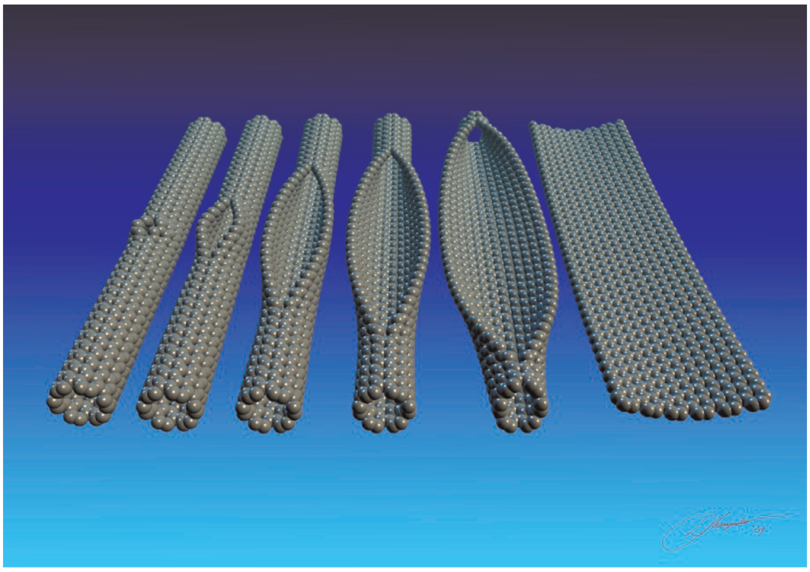

Figure 3. Longitudinal splitting of a carbon nanotube results in a graphene nanoribbon.[11−13] The figure was prepared and signed by D. Kosynkin. Reproduced with permission from ref 11. Copyright 2009 Nature Publishing Group.

the basis for years of future research and support because he was able to open doors into areas of nano-based research that few others could conceive. I have learned to appreciate those especially creative colleagues; whenever they leave my group, I miss their keen insights.

What Is the Genesis of the Creativity? Trying to understand what might have been the source of Wally Scrivens' creative talent, I once asked, "What was your upbringing like? What kinds of activities did you do as a kid?" He replied that he had "often played with chemicals"..."back in the days when you could buy real chemicals from the local pharmacy." Although he did well in school, he never worked very hard at schoolwork until college. As a child, he described how he made his own gunpowder starting from charcoal that he prepared by burning wood, and how he had tried to replicate Damascus steel through a forging process in his basement. He described explosions and fires. Being a parent myself, I asked, "Didn't your parents mind the dangers involved in your antics?" His reply was that his parents were too busy and distracted with their own life struggles to be there to question or to stop him from experimenting. Maybe that is a clue! In our efforts to protect our children from harm, do we curb their creative maturation? Certainly, giving young children freedom to explore with explosions and furnaces can result in a natural selection process that parents rightly guard against. But in this litigious and extreme-safety-conscious generation, are we inhibiting the creative development of our youth? Though I never tried to make Damascus steel as a child, I surely did my share of blowing things up, making fire-shooting guns, and I was constantly modifying my bicycle with longer, home-built front forks to fashion into choppers, and that was before I had my hands dissecting minibikes or making week-long modifications to my car—back in the days when 50% of the volume under the hood was empty space. And I too had a childhood chemistry set back when a child could easily poison him or herself with the chemicals afforded. Is creativity birthed through childhood freedom to explore?

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Chris Husband was a "late-bloomer" academically, not rising to a competitive level until high school. But since Chris was very young, his dad, whom I have met on a several occasions, had presented him with math problems and puzzles simply as part of their general conversations. They have a running joke about a problem that Chris solved in about 15 or 20 min when he was a kid. His dad had worked on it for 15 or 20 years, but now claims that he *really* only worked on it for about a minute per year, so it is the same. Apparently, Chris' dad did a great job in creating an intellectually stimulating atmosphere. (I wish that I had been more like Chris' dad when interacting with my four children.) They still do this, though now Chris usually gives the problems to his dad. I do not know if this was inherited or learned from his dad, but Chris will not accept a convention or rule of thumb without understanding why it should be followed. That habit can be frustrating for others, but that personality trait has served Chris well in science.

For Dmitry Kosynkin, life in the Soviet Union was different. Of his childhood he writes, "My grandfather's makeshift photographic lab, that he would unfold from a corner of his tiny Khrushchev-era bathroom to conjure up magical images on what appeared to be simple sheets of glossy paper, was giving me a glimpse of the future love of my life: Her Majesty, Chemistry. It was the time when I saw my first chemical reactions and was forever imprinted with the sense of amazement. I had a fair share of tin soldiers, plastic Indians and cowboys, Meccano sets, Legos and even a German electrical model railroad later on, but the most coveted present ever was the Young Chemist's Kit that I managed to beg from my mother at age 12. It could be the tinkering with Meccano and Lego combined with growing `seaweed' from copper sulfate and sodium silicate, cramming my head full of crazy futuristic ideas of the sci-fi books and drawing and painting almost every day, that created some unusual connections in my brain that sometimes allow me to see things that other people overlook. I am grateful to my parents for being interested enough with their own lives to keep from trying to live vicariously through me and telling me how I should see the world and interact with it."

How Shall We See the Top Ideas in Nanoscience? That is a simpler question than the genesis of creativity. For one thing, let us work in fields outside our expertise so that we can bring foreign ideas to bear in diverse areas. Sure, this could mean that we show our ignorance of the new area for a while, and I have oftentimes been taught the basics by reviewers of our manuscripts. But swallowing our pride, we pressed on. And let us surround ourselves with talented and inquisitive students. Every once in a while, an unusually creative young mind will come along that can stimulate us to much grander things than we could have imagined. When those atypical ones arise, let us expect from them what they can deliver, and do not expect from them what they cannot deliver, lest we exasperate them and us.

Where the Praise for Our Nanoscience Belongs. There are so many of my other students and postdocs and colleagues who are praiseworthy. The ones noted here are representative of many, and I even feel a bit uneasy naming those above for fear that the others would feel that I view them as inferior. Not so! When I think of the work of co-workers such as the ones who directed our nanomedicine program;[18] the one who introduced our group to graphene electronics;[19] those original developers of nanocars and motorized nanocars;[20,21] the one who first made clean graphene from solids;[22] the young man that persisted to delineate the silicon oxide switching mechanism in spite of the opposition;[23] the postdoc who gave me a taste of theory and a crash course in electronics;[24] Rick Smalley whose death in 2005 thrust me into gas-phase research through my having to see his students through to their graduation;[25] the many that made the advances in silicon surface chemistry and molecular electronics;[9,26,27] Dustin James—the one who really works with the students to write every manuscript and every proposal, and many others; all that I can say is that I am a man most blessed. When I give seminars, I often try to underscore the contributions of those that had the special insight and those that pulled it all together to spur so many of our group's advances in nanoscience. But academic research advising can be an odd endeavor. When I really start praising the work of individual students, the audience then views me as being all the more magnanimous because they start adding "humble" to the list of adjectives—but in my case, it is not humility, it is truth. I am most often a cheerleader, a motivational speaker, and a financier; others conceive of the most interesting projects, and still others develop the full data sets and write the manuscripts. Sure, I make corrections and some suggestions, but those are usually of lower impact. Most often, professors seem to receive the accolades and prizes for the work of their students. And that is certainly the case with this inaugural ACS Nano Lectureship Award. To those who did the conceiving and the heavy-lifting in the trenches, thank you!

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