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This Portrait of Marie Curie

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A good portrait of a person should portray them without the need for words, and this one hanging in my laboratory at the University of California-Berkeley is no exception. I often ask my students, especially those seeking a second opinion on the quality of their work, to look into Marie Curie's eyes in the portrait and tell me what she is saying to them. After their initial puzzled expressions, they generally respond with uncertainty. I encourage them to look more deeply into her eyes and ponder her message, but their answers remain unchanged. This is when I suggest: She is trying to tell us that we can do better, much better, and now it is time for us to get it done. Consequently, my students and I have used this portrait as an inspiration to strive for excellence in our research and, more specifically, in my role as a mentor.

While much has been written about this extraordinary individual, I can contribute little beyond the existing insights into Marie Curie's life and scientific work. Although this article is about the role of mentoring in discovery and not an

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article about Marie Curie per se, it is useful to remark how little has changed since Marie Curie established her laboratory and mentored her researchers. She understood, as we do now, that effective mentorship is the key to innovation and the foundation of a thriving research enterprise. Her methods and ideas have largely stood the test of time. Today, in research-strong countries, there exists a robust mentoring system that we often take for granted. However, given the challenges we face today, I find that this invaluable mentoring system is at risk of being undermined by an overemphasis on superficial politeness. How can we effectively mentor and nurture the next generation of intellectually curious and creative students amidst popularity contests centered around 'likes', 'views', and 'followers'? It is difficult to discern the sincerity of these expressions and whether they play any role in genuinely improving our interactions, but unfortunately, they create noise from under which facts struggle to rise. Mentors need to be cautious about giving this 'fluff' any credibility when mentoring research students.

I believe that practicing truth in mentoring serves as an antidote to these superficial expressions of support. Those of us who have overcome obstacles in our lives and solved long-standing problems in our professions are all too familiar with the arduous journey inherent in stories of success and triumph. The experience of failure and challenge as a stepping-stone to success is a key component of the tradition of self-improvement, which many attribute to individual's innovation and productivity. Effective mentorship requires providing direct, truthful, and compassionate feedback to students, helping them overcome difficulties in their work and laboratory lives. Open and honest communication with students about our thoughts and feelings as their research advisors is crucial for fostering critical thinking, creativity, resilience, and ultimately, independence.

In this essay, I will share a series of vignettes illustrating my experience with challenging situations in my laboratory, which I believe are common occurrences in synthetic chemistry-oriented research groups. The overarching theme of these vignettes is the importance of conducting experiments regardless of any preconceived notions held by reasonable chemists. I have titled each vignette to emphasize the paramount importance of performing the experiment. Noting that the human element in discovery is vital for uncovering what many have missed and for pioneering new frontiers in science. It encompasses determination, hard work, and faith in the power of experimentation. Ultimately, these vignettes are about mentoring students to do the experiment.

PIONEERS BEYOND BORDERS

I wish to bring attention to Marie Curie's courageous journey from Poland to France for her studies. It required her to leave her family and the safety of her home in pursuit of a better life. This brave undertaking is mirrored in the experiences of many modern graduate students, who traverse oceans to join research laboratories in hopes of expanding their knowledge and improving their family's circumstances. I was deeply moved when one of my own graduate students referred to our research group as their "new home" during a Christmas party speech. This sentiment reminded me of the gravity of my role as a mentor and the dedication required to make a positive difference in their lives. Marie Curie herself valued the collaboration of researchers from diverse backgrounds and nationalities, actively recruiting international researchers and prioritizing the inclusion of women. Today, we continue to emphasize the importance of blending national origin, race, and gender in the scientific community.

However, challenges such as visa restrictions and lingering racial and gender disparities at universities, particularly in faculty hiring, persist. Let us draw strength from Marie Curie's words, "Nothing in life is to be feared, it is only to be understood. Now is the time to understand more, so that we may fear less," as we work together to overcome these obstacles and foster a more inclusive scientific community.

THE PERIL OF RATIONALIZING EXPERIMENT FAILURE

The phrase "the experiment didn't work" is all too familiar in scientific research, often accompanied by a litany of seemingly reasonable explanations for the failure. However, this rationalization can be detrimental to the process of discovery. As Marie Curie once said, "I am among those who think that science has great beauty." Her passion and dedication to understanding the unknown should serve as a reminder to researchers that failures are part of the journey.

As a mentor, I have developed a strategy to address this issue when students come to me with 'failed' experiments. My first questions are to ask what they tried and how many attempts they made. Often, I find that students have made fewer attempts than I would have expected. I then remind them of the great distances they have traveled to join my research group and pursue groundbreaking discoveries, just as Marie Curie did in her own journey from Poland to France. This usually inspires a renewed enthusiasm and commitment to additional experimentation.

For students who persist in justifying experiment failures, I challenge them to provide scientific proof for their reasoning. Typically, their justifications lack sufficient precedent or data, leading to the decision to conduct further experiments. I think embracing the idea that an experiment doesn't work because we have not made it work is crucial to fostering a culture of discovery. Justifying failure can be an obstacle to progress.

AVOIDING PREMATURE JUDGMENTS IN EXPERIMENTS

The optimal balance between mentorship and student autonomy can lead to fruitful outcomes in scientific research. In the mid-1990s, when metal-organic framework (MOF) chemistry was in its infancy, a student in my group discovered colorless cubic crystals that turned white and lost their shape when exposed to air. Believing the compound to be unstable and uninteresting, the student disregarded it. As a mentor who frequently checks in with students about their daily observations, I was captivated by this student's description of the disintegrating crystals. I advised them to maintain the crystals' wetness by keeping them in their 'mother liquor,' which led to the discovery of MOF-5 — an archetypal MOF with record-breaking porosity.

Reflecting on this breakthrough, I considered the importance of striking the right balance between guidance and autonomy in the mentor-student relationship, much like how Marie Curie mentored her own daughter, Irène Joliot-Curie, who later became a Nobel laureate herself. We want students to explore and make decisions on the spot as to which observation to pursue further, yet we should also be close enough to participate in the decision process, at least for those observations we deem of potential import.

ELEVATING EXPERIMENTS TO ACHIEVE GREATER IMPACT

While many researchers can execute good experiments, fewer possess the ability to conduct great ones. Transforming a good experiment into a great one demands extensive knowledge of the research landscape, an understanding of its connections to other scientific areas, and a deep-rooted belief in the potential for exceptional outcomes. This principle is exemplified by a student who sought to create MOFs with large pore openings by expanding the organic linker. After successfully adding a second and third phenylene unit to the linker, I encouraged the student to add a fourth unit to potentially achieve a record-breaking pore opening in crystals.

The student not only accomplished this feat but also independently continued the work, adding five, six, seven, eight, nine, ten and eleven phenylene units. This exceptional achievement illustrates the power of challenging and inspiring students, who, in turn, deliver remarkable results through hard work and innovative experimentation. Indeed, I discovered that my students expect me to challenge them, and accordingly they enjoy the sweet success delivered through hard work and thoughtful, impactful experimentation at the next level. Marie Curie's wisdom captures the essence of this vignette: "One never notices what has been done; one can only see what remains to be done."

THE POWER OF OBSERVATION IN EXPERIMENTAL RESULTS

Countless discoveries have arisen from keen observation of minute changes in experimental results, a concept exemplified by Marie Curie's relentless pursuit of knowledge in her own experiments. The discovery of covalent organic frameworks (COFs) illustrates this aspect of experimentation. Despite long-standing skepticism by the chemistry community about creating infinite, extended organic structures by linking organic molecules through covalent bonds, we set out to develop COFs and overcome their crystallization challenge. For six years, incoming students were given the opportunity to work on this ambitious project. Most faced failure, with their reactions producing amorphous and ill-defined solids.

Surprisingly, it was an undergraduate student who ultimately achieved success with COFs. The student's keen observation of a nearly invisible diffraction line in an X-ray pattern led to the first crystallized COF (COF-1 reported in 2005). The student further found that the length of the reaction tube affected the sharpness of the diffraction line. Based on this seemingly meaningless observation, I was able to deduce that the pressure caused by water (the byproduct of the reaction) was controlling the reversibility of the formation of the COF and in turn I accordingly recommended to the student to use it as a handle in controlling the crystallization of the COF.

N.B. : As a mentor, it was crucial to ensure for those dedicated graduate students, who pursue high risk but non-yielding projects, that they are also involved in other projects to enable them to complete their theses and publish papers. Striking a balance between challenging and fruitful projects was essential, as was maintaining the students' motivation and ethical considerations. In the end, however, some undergraduates are eager to take on high risk projects, and this is to be encouraged.

A MENTOR STATEMENT OF A RESEARCH PROBLEM IS CONSEQUENTIAL

Reticular chemistry requires a researcher to imagine a structure they wish to make, and to reduce such target structure into its geometric building units. Although I have articulated this in publications and by now it is a common practice, somehow when I described the molecular weaving project (weaving is interlacing of long threads) to an incoming graduate student, I only shared the imagined structure part (the problem) but not the reduction to the building unit part (the solution).

I began by showing an illustration of a woven pattern and asking the student to think about making such pattern as a chemical structure. Naturally, a starting student would not have had background in reticular chemistry and thus their tendency to gravitate towards thinking that threads must be made first and then somehow by a 'miracle' interlaced to make the woven pattern. This approach necessarily leads to an "it will not work" conclusion. For that reason, not only new graduate students deemed the project undoable, but also most chemists I have shared this idea with.

In thinking about how I could get someone to take on this project, I realized that unconsciously I have been giving them only the target structure without a strategy for achieving it. Although, the target weaving structure was inspiring to the student and decidedly a worthy goal, without a credible proposal of a strategy for realizing it, no students wish to take the risk of venturing into it. This is not because graduate students are not adventurous but rather because it's easier to follow a path where results can be reasonably expected. Finally, I proposed to one student that they make a molecule that approximate the crossing — common in weaving, then functionalize that molecule with the appropriate organic group for reticulating it with the corresponding organic linkers. Without hesitation the student made these units and reticulated them using COF chemistry to produce the first molecular weaving.

In a way, we were able to make a woven structure by linking the crossings rather than by having to weave the threads. The desired result was achieved but by a much simpler path enabled by reticular chemistry thinking. Thus, how the mentor states the problem to a student is directly related to how easily it can be solved and in turn whether that student picks up the project at all. The mentor's wisdom in breaking down complex problems into manageable parts can serve as a guiding principle for mentors and students alike.

THE HEROES IN OUR LABORATORIES

Marie Curie's perseverance in the face of adversity inspires us to keep observing and learning, even in seemingly impossible situations. Over the last thirty years of my career as mentor and independent researcher, I have had the singular honor to work with researchers in my laboratory who were fearless and frontier scientists at heart. I called them expeditionary scholars. These have the characteristic of being thirsty for challenge and whenever I raise the bar for their work, they go right through it and showed a higher level of performance. They are our heroes in science because they persevere and break down prevailing dogmas and imperfect scientific practices. These are the students who see no borders in their pursuit of scientific discovery.

Such heroes are responsible for widening the scope of chemistry beyond its current borders. They exist in many laboratories, and they are the motivating force for our commitment to mentoring and dealing with all the drama that comes with raising the bar in our research groups and our expectations of excellence. I wish to cover a couple of contributions made by my heroes that everyone will recognize today to have been a bold departure from the prevailing state-of-affairs at their time of discovery.

First, measurement of the first gas adsorption isotherms of MOFs, which many chemists considered not chemistry at the time. These isotherms were measured by a researcher in my group who had to build an adsorption apparatus to make the measurement of nitrogen uptake in the pores of a MOF. The apparatus required a weight balance with nanoscale accuracy. The researcher was successful in getting a nanobalance, originally used by a retiring professor to dose oxygen for catalysis. The balance was coupled to a Schlenk line to allow for incremental dosing of nitrogen gas at 77K and to determine the gas uptake and architectural stability of the first porous MOFs (MOF-2 and MOF-5). This advance formed the basis of what every reticular chemist uses today as a common practice to evaluate and study the permanent porosity of their MOFs and COFs.

Second, building practical water harvesting devices in a synthetic chemistry laboratory, an activity that many complained was not within the realm of chemistry. To build such devices requires expertise in air flow, mass transport into the MOF, and energy consideration of the entire system. In other words, it needs at least chemical and mechanical engineering expertise. These competencies are not found in a typical chemistry research group.

Driven by the promise of harvesting water from the desert, three researchers in my group teamed up to make this a reality. They built a water harvesting device and showed its feasibility in a laboratory setting. I raised the bar by asking them to show its viability and performance in the desert. They scaled-up the device and journeyed to the desert and showed it to work successfully under real desert conditions.

We realized that without studying water harvesting in the field, it is difficult to appreciate the complexities of the water harvesting problem. Thus, these desert experiments were instrumental in building energy efficient devices, and without these onsite trials it wouldn't be possible to inform the materials design and the basic science being done back in the laboratory.

PROSPECTING THE FUTURE — ARTIFICIAL INTELLIGENCE IN CHEMISTRY

Artificial intelligence (robotics, data science and machine learning) is taking the world by a storm. It is incumbent upon us as chemists to find ways of integrating this new tool into our research. There is no doubt that AI will continue to grow in importance and eventually in impacting chemistry. AI for chemistry is not a fully developed field, and therefore any first steps taken to use and develop these tools for chemistry will have impactful results. This is true provided good questions can be articulated. Here, graduate students and postdoctoral fellows (the heroes discussed above) are critical in helping a laboratory take its first steps in deploying these tools. Some would go as far as to say that AI for chemistry is a necessary condition for the survival of chemistry in a world where almost every other field of study and every domain of society is being transformed by it.

I strongly believe in this direction for chemistry in general and specifically for reticular chemistry. The ability to rapidly identify the conditions under which materials can be made and connect that with specific applications by correlating structures with properties will be greatly aided by AI. Accordingly, Professor Jennifer Chayes (Founding Dean of the College of Computing, Data Science, and Society at UC Berkeley) and I have recently established the Bakar Institute of Digital Materials for the Planet. Its mission is to integrate AI tools into the science of building new materials to solve climate challenges. This interface is underdeveloped and computer scientists and chemists are not yet comfortable with reaching out to each other. We hope this new institute will function as a bridge to allow meaningful collaborations to be established between the two sides.

This initiative was entirely motivated, and the first steps taken by an incoming graduate student in my laboratory whom after I had proposed several chemistry-based projects for them to pursue, the student turned to me and declared that AI is ideally suited for these projects. Having already written an article on establishing digital reticular chemistry but still knowing close to nothing about the interworking of AI methods, I was excited by the prospect of such a student to take on the challenge under my mentorship. Quickly the student taught themselves programming and the mathematics behind machine learning models and together we are now developing what we call the digital innovation cycle. This is an experimental-computation cycle aimed at automating and speeding the development of new materials for climate applications.

We are yet to report on this approach, but I can say that it has been transformational to our efforts and infectious to the other students in my laboratory. Many initially doubt the effectiveness of such methods in chemistry, I believe these AI tools will save time, materials, and ultimately allow us to do chemistry sustainably. More on this in the future.

THE HUMAN ELEMENT IN SCIENTIFIC DISCOVERY

The human element in scientific discovery, characterized by determination, hard work, and belief in experimentation, plays a pivotal role in pushing the boundaries of knowledge. Each of the vignettes illustrates how mentor-student relationships based on challenge, struggle, and sometimes friction can lead to groundbreaking discoveries. As mentors, we must manage any friction while adhering to norms of civility.

When the mentor-student interaction is free of hierarchy, the struggle transforms into the joy of research, mentoring, and learning. On the other hand, without these struggles hardly anything worthwhile could be learned or achieved. As the old proverb states (paraphrased here): gems cannot be polished without friction, nor a person perfected without trials. This has been reiterated by so many in so many forms not the least of whom is Marie Curie who once said: “I was taught that the way of progress was neither swift nor easy.”

My hope is that this portrait of Marie Curie will come to symbolize the courage of our students who dive into research and all its uncertainties, and the power of mentoring in motivating students to do the experiment and therefore make world-changing discoveries. Now you see how much this portrait means to me and how much it compels all of us to go beyond superficial politeness in our obligations towards our students. Namely, to foster a mentor-student interactive culture that is free of superficial politeness, direct and not sugarcoated, and elevating the mind by encouraging free thinking especially in dealing with the unpredictable, arduous journey that so often precedes discovery.