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Perspective on Green Chemistry: The most challenging synthetic transformation

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Synthetic transformation. When any chemist thinks about the phrase, 'synthetic transformation', it immediately conjures up images of some of the greatest accomplishments in the field of chemistry over the past century and a half. The brilliant and creative, sometimes Herculean effort to convert a readily available feedstock into an almost inconceivably complex molecule has been one of the most worthy areas of pride within the field of chemistry. However, the phrase 'synthetic transformation' literally means simply 'man-made change'. Some of the most challenging changes that will be needed in the years to come will not only take place in the flasks on our bench, but in the minds and the perspectives of the chemists themselves.

In 2009, it is difficult if not impossible to name an aspect of the field of chemistry that is not doing excellent work in the area of green chemistry. Physical, physical-organic and biophysical chemistry have taken leadership roles in a range of green chemistry accomplishments, including new solvent systems and new approaches to biomaterials. Organic chemistry has seen a whole new branch of endeavor in green synthesis that is applicable to a wide range of targets from pharmaceuticals to dyes. Inorganic, organometallic chemists and surface scientists have incorporated green chemistry approaches into new catalysts and energy systems. Polymer chemists have introduced new materials, polymer syntheses, and processing methods that have been invented through a green chemistry framework. The list of accomplishments in the various sub-disciplines could go on.

In recent years, new research centers and research networks have blossomed across Europe, North America, Asia, and Oceania with emerging efforts in South America and Africa. Several reputable scientific journals dedicated to the topic have emerged over the course of the past decade and academic programs at universities are too numerous to list.

With all of this success—the synthetic transformation is not complete

Green chemistry research still makes up a relatively modest percentage of all research in chemistry currently being conducted. The efforts in green chemistry are fragmented and not cohesive. Our top chemistry Ph.D. candidates can graduate without having any formal training in the human or ecological consequences of the tools of their trade. It is for these reasons and more that essential steps must be taken for the full power, potential, and integration of green chemistry to be realized.

1. **Appreciation of the great scientific challenge that confronts us.** Addressing the unsustainable trajectory of the planet has often been thought to be one that is best dealt with through governmental action, behavioral chance, and public policy. While all of these have important roles to play, the scientific community, and specifically the chemistry community, needs to be profoundly aware that the generation of new chemical products and processes is essential to sustainability. In the absence of new materials for alternative energy, food production, water purification and medicines, there are no policies that can be put in place to avoid catastrophic consequence. The magnitude and urgency of the scientific challenge cannot be understated.
2. **Understanding by all chemistry practitioners that the basis of many of the world's greatest challenges can be significantly impacted positively at the molecular level**. When the chemistry community is fully conscious of the challenge that confronts the world, the next step is to be fully aware of the power of chemistry to address it. Just as the basis of the various hazards we face can be found at the molecular level, so too can the solutions. Through the practice of incisive forward-thinking Green Chemistry, the next generation of substances that are the basis of our economy can be designed so as to be fundamentally sustainable.
3. **Exploit the power of design.** Design cannot be done by accident. It is a statement of human intention. For too long the chemistry community has let the 'performance criteria' be defined for them. Pharmaceutical targets are identified and given to the synthetic chemist to make. New adhesives, dyes, or fuels are found to have desirable performance, and then the task of synthesizing them is given to the chemist. Those who are endowed with the ability to create new molecules are entrusted with the responsibility for the consequences of those new molecules on humans and the environment. Too much knowledge exists for the chemistry community to claim ignorance about the ability to design substances that are safer and more sustainable.
4. **Think across life-cycles.** As we develop our chemistry, we need to not merely think about production and use, but rather, where

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did the starting materials come from and what will happen to these substances at the end-of-life? Research chemists can no longer comfort themselves by thinking that since they are only making a few milligrams, any adverse consequence need not be considered. One would need to hope that their chemistry never finds broad use or application in order for that rationale to be legitimate.

5. **Develop systems thinking and holistic chemistry.** Reductionism has brought us to both tremendous heights of creativity and tremendous depths of understanding. Compartmentalization and fragmentation of our chemistry has contributed to the various problems that have arisen. If we are only to look at material efficiencies, for example—which historically is the case—we would miss a host of issues related to energy, toxicity, persistence, and bioaccumulation to name a few. The *Twelve Principles of Green Chemistry* set out a design framework a decade ago and significantly laudable work has been done in academia and industry to advance the field. Much of it has been focused on specific principles. In order for Green Chemistry to reach its power and potential, it will require looking at the *Twelve Principles* as a cohesive system; a system that through thoughtful design creates synergies amongst the principles rather than trade-offs.

It is worth noting that the synthetic *chemical* transformations that will lead us to a more sustainable civilization of products and process that protect our finite feedstocks from depletion, preserve rather than degrade our ecosystems, design away from bioaccumulation in our bodies, maintain our climate, and protect our reproductive capacity, are only going to be possible if the other synthetic transformation—the transformation of the discipline of chemistry and how we choose to pursue it—takes place.