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John received his BS in Chemistry from UMASS Boston, and his PhD in Chemistry from Princeton University. After working at the Polaroid Corporation for nearly a decade, he then served as tenured full professor at UMASS Boston and Lowell (Chemistry and Plastics Engineering). In 2007 he founded the Warner Babcock Institute for Green Chemistry, with Jim Babcock (a research organization developing green chemistry technologies), and Beyond Benign with Amy Cannon (a non-profit dedicated to sustainability and green chemistry education).

While a senior research group leader at the Polaroid Corporation (1988-1997) Warner coauthored the defining text for the field of Green Chemistry with Paul Anastas and codified the 12 Principles of Green Chemistry. He is the editor of the journal "Green Chemistry Letters and Reviews". Warner is on the advisory panel for the Ellen MacArthur Foundation's New Plastics Economy has been elected a full member of the Club of Rome and is an advisor for Parley for the Oceans where in 2016 he helped create the technology for the Adidas Parley Recycled Ocean Plastics Shoe. He has served as sustainability advisor for several multinational companies. His research and publications in synthetic organic chemistry, noncovalent derivatization, polymer photochemistry and low temperature metal oxide semiconductors has provided the foundation for his theories of what he calls "entropic control in materials design".

The Warner Babcock Institute for Green Chemistry (WBI) is an independent 42,000 sq ft (4000 sq m) research laboratory in Wilmington, Massachusetts fully equipped with state-of-the-art chemistry and engineering equipment. With nearly 250 patents across more than 70 patent families, he has worked with over 100 fortune 500 companies helping to invent commercially relevant (high performance and appropriate cost) green chemistry technologies across all sectors of the chemical industry. His chemistry inventions have served as the foundation for several new companies, examples include: Collaborative Medicinal Development (ALS Therapy, Phase II Clinical Trials), Hairprint (hair color restoration), Collaborative Aggregates (Delta-S and Delta-Mist, asphalt warm mix, rejuvenator, & spray coat), Ambient Photonics (Lowlight Indoor Solar Energy devices for IoT and BIPV) Formaldehyde and Isocyanate Free wood composite adhesive, and Lithium Cobalt Battery recycling technology.

In 2007 Warner cofounded the nonprofit organization Beyond Benign with Amy Cannon. Collocated at the WBI labs in Wilmington, MA, Beyond Benign creates curricula and training for K-12 and university educators to incorporate concepts of green chemistry and sustainability to improve STEM education. Beyond Benign administers the Green Chemistry Commitment, asking University Chemistry departments to incorporate the principles of green chemistry into their mainstream curricula.

John has received awards as an academic (PAESMEM – President G. W. Bush & NSF, 2004), industrial chemist (Perkin Medal – Society of Chemical Industry, 2014), inventor (Lemelson Ambassadorship – Lemelson Foundation & AAAS) and for governmental chemicals policy (Reinventing Government National Performance Review – Vice President A. Gore & EPA, 1997). He received the American Institute of Chemistry's Northeast Division's Distinguished Chemist of the Year for 2002 and the Council of Science Society President's 2008 Leadership award. Warner was named by ICIS as one of the most influential people impacting the global chemical industries. In 2011 he was elected a Fellow of the American Chemical Society and named one of "25 Visionaries Changing the World" by Utne Reader. He serves as Distinguished Professor of Green Chemistry at Monash University in Australia and in 2017 the German Ministry of Economic Affairs and The Technical University of Berlin announced the naming of "The John Warner Center for Green Chemistry Star-Ups" in his honor.

BEFORE THE UNITED STATES HOUSE OF REPRESENTATIVES

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

SUBCOMMITTEE ON RESEARCH AND TECHNOLOGY

Benign by Design: Innovations in Sustainable Chemistry

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Chairwoman Stevens, Ranking Member Baird, and members of the Subcommittee, thank you for this opportunity to discuss the subject of Green Chemistry, and its importance to protect our nation's environment while maintaining and growing our industrial competitiveness.

1. Introduction

My name is John Warner. I have been a professional chemist for 31 years. I spent 1988-1996 as an industrial chemist leading exploratory research efforts at the Polaroid Corporation. I spent 1996-2007 in academia reaching the rank of tenured full professor of chemistry and plastics engineering in the University of Massachusetts system where I helped create the world's first PhD program in Green Chemistry. Since 2007 I have been the President and Chief Technology Officer of the Warner Babcock Institute for Green Chemistry and cofounder of the educational nonprofit organization Beyond Benign.

I am a chemistry inventor with nearly 250 published US and international patent applications. Over the years I have collaborated with more than 100 companies helping them invent cost effective green chemistry solutions. My green chemistry inventions have also served as the basis of new companies including a hair color restoration company[1], an asphalt pavement rejuvenation technology[2], a pharmaceutical company with an ALS drug in clinical trials[3], and a solar energy company[4]. Additional inventions include water harvesting/desalination[5], formaldehyde/MDI free engineered wood composites[6], bioinspired adhesives[7], biobased furniture cushions[8], aqueous based lithium battery recycling[9], anti-cancer drugs[10] and Alzheimer's drugs[11]. I provide this list of inventions at the outset to illustrate the point that green chemistry plays an important role in the innovation of commercially relevant technologies.

2. Some Background

Society is necessarily dependent on chemistry and chemicals. The foods we eat, the clothes we wear, the materials that allow us to package and protect goods, the electronic devices that we use, and the vehicles we drive, are all examples of things in everyday life that are made up of chemicals.

With all the positive advances in our society that chemistry has provided there have also been some problems as well. Some chemical products and manufacturing processes have negative impacts on the environment, climate, wildlife and human health. It is important to note that not all chemical products and processes have negative impacts, some do, and some don't.

Chemicals are also the basis of everything in the natural world as well. The water we drink, the air we breathe, the plants, animals, birds, insects, fish and fungi, like industrial products, they are all made up of chemicals too. The ubiquity of chemistry is why chemicals simultaneously provide the foundation of our economy and the basis of the health and wellbeing of humans and the Earth's ecosystems. When people discuss wanting products and environments to be "chemical free", they do not understand that everything, good and bad, is made of chemicals. They really do not seek a world absent of *chemicals*, they want a world free of *hazardous chemicals*. An important question then to ask is "why can't all chemical products and processes be free of negative impacts on human health and the environment?"

3. My History in Green Chemistry

In the early 1990's Dr. Paul Anastas, then at the United States Environmental Protection Agency initiated a program that he called "Green Chemistry"[12]. At that time, I was a chemist inventor working at the Polaroid Corporation. My industrial career was progressing quite successfully. I had many patents and received several awards as a chemistry inventor. One of my inventions at Polaroid was proceeding through the TSCA[13] process on the way towards commercialization.[14] This found me interacting with Dr. Anastas at the Office of Pollution Prevention and Toxics to understand the various EPA regulatory processes. My Polaroid invention was a good example of an industrial process that was "benign by design". I started collaborating with Dr. Anastas and the US EPA's nascent Green Chemistry program.

At about the same time my personal life met with disaster. I lost my two-year-old son John to a birth defect.[15] In anguish, I asked myself if it was possible that a material I had worked with in the lab at some point in my career was responsible for my son's disease and ultimate death. I realized that during my four years of undergraduate education and four years of graduate education in chemistry, I never had any classes that prepared me to answer this question. The answer to the question was less important to me than the realization that I did not have the ability to answer it. Did something I worked with have the potential to cause my son's birth defect? I came to the startling realization that no university chemistry programs in the world at that time required students of chemistry to have any training in understanding the relationships between molecular structure and negative impacts on human health or the environment.

4. The Principles of Green Chemistry

Over the next few years Paul Anastas and I wrote the book: "Green Chemistry: Theory and Practice".[16] The definition of Green Chemistry is "the design of chemical products and processes that reduce or eliminate the use and/or generation of hazardous substances." In order to help make Green Chemistry industrially relevant and straightforward to implement, the book also expands a set of 12 principles. These principles are written in the language of chemistry. The intent is to help relate the molecular structures and mechanisms of chemistry during the design phase of a product, to avoid the use hazardous materials.

The 12 Principles of Green Chemistry

1. Prevention. It is better to prevent waste than to treat or clean up waste after it is formed.

2. Atom Economy. Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.

3. Less Hazardous Chemical Synthesis. Whenever practicable, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment.

4. Designing Safer Chemicals. Chemical products should be designed to preserve efficacy of the function while reducing toxicity.

5. Safer Solvents and Auxiliaries. The use of auxiliary substances (solvents, separation agents, etc.) should be made unnecessary whenever possible and, when used, innocuous.

6. Design for Energy Efficiency. Energy requirements should be recognized for their environmental and economic impacts and should be minimized. Synthetic methods should be conducted at ambient temperature and pressure.

7. Use of Renewable Feedstocks. A raw material or feedstock should be renewable rather than depleting whenever technically and economically practical.

8. Reduce Derivatives. Unnecessary derivatization (blocking group, protection/deprotection, temporary modification of physical/chemical processes) should be avoided whenever possible.

9. Catalysis. Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.

10. Design for Degradation. Chemical products should be designed so that at the end of their function they do not persist in the environment and instead break down into innocuous degradation products.

11. Real-time Analysis for Pollution Prevention. Analytical methodologies need to be further developed to allow for real-time in-process monitoring and control prior to the formation of hazardous substances.

12. Inherently Safer Chemistry for Accident Prevention. Substance and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.

5. Benign by Design

It is important to underscore that green chemistry specifically focuses on the *design* of new materials and processes. While regulating, measuring, monitoring, characterizing and remediating hazardous materials is important for protecting human health and the environment, green chemistry seeks to create technologies that avoid the necessity of doing any of this in the first place. If technologies are created using green chemistry, the various costs associated with dealing with the hazardous materials is avoided. It just makes smart business sense.

For a green chemistry technology to succeed in the marketplace it not only must improve impacts on human health and the environment. It must also have excellent performance and appropriate cost. If the technology doesn't work well, no one is going to use it. If the technology costs too much, no one is going to buy it. The only person who can truly address these issues is the inventor. After the technology is invented and on its path to commercialization, it is too late. If the product contains hazardous materials, the only way to deal with them is to mitigate exposure, and that always comes at an additional financial cost.

The financial and commercial benefits are obvious to industry, once green chemistry is understood. The problem however, as I realized when reflecting upon the potential causes of my son's birth defect, was that the traditional chemistry curricula at universities were completely void of this information. It is one thing for a company to *want* to make products that are safer for human health and the environment. The economic and ethical benefits are straightforward. Unfortunately, I realized companies didn't have the *ability*. The R&D work force simply didn't have the skills or training to invent products that are safe for human health and the environment.

6. Green Chemistry and Academia

While my career at Polaroid was very promising, I realized that green chemistry was more of an issue with the field of chemistry in general rather than just in industry. I left Polaroid and I went to teach at my alma mater, the University of Massachusetts at Boston. I began to integrate the principles of green chemistry into my teaching and research. I found that my students had better performance and understanding of chemistry concepts when green chemistry was integrated into the curricula. In 2001 we began the world's first PhD program in green chemistry. The degree program was like a typical chemistry graduate program but there were added classes in mechanistic toxicology, environmental mechanisms and environmental law and policy. The students passing through the various green chemistry activities at UMASS Boston had significant success getting jobs in the chemical industry.

I had an active research program at UMASS with post-docs, graduate students and undergraduate students. I routinely asked my research students to visit local K-12 classrooms in the metropolitan Boston area. Over the 10 years I was at UMASS, my students and I made hundreds of trips to different schools and classrooms. Having my university research students share their green chemistry projects and personal passion for green chemistry with the K-12 students was quite transformational. The K-12 students were under the impression that chemistry was solely the cause of all the environmental problems in society. When they learned from my research students that the only path to a safe and sustainable future is by inventing better technologies with green chemistry, it completely changed their perspective. It also had significant impact on my research students as well, to understand and respect their individual abilities to share part of themselves to the greater community.

In 2004 I was blessed to receive the Presidential Award for Excellence in Science, Mathematics and Engineering Mentorship[17] (PAESMEM) by President George W. Bush and the National Science Foundation for helping bring woman and underrepresented minorities into the chemical enterprises through green chemistry.

7. Green Chemistry and Sustainable Chemistry

Both sustainable chemistry and green chemistry are important for the future of the society. Sustainable chemistry is a large umbrella concept that addresses the many aspects of the chemical supply chain, including manufacturing improvements, remediation technologies, exposure controls and recycling technologies. Green chemistry specifically focuses on the inventive process to reduce or eliminate the use and generation of hazardous material in the first place. One way to look at it: sustainable chemistry focuses on what a technology *does*. green chemistry focuses on what a technology *is*. Green chemistry addresses issues with the solvents, the catalysts, the toxicity, the renewability, the biodegradability. Each of the 12 principles of green chemistry identifies the compositional aspect of the product or process.

For example: a solar energy panel is an important sustainable chemistry technology. The world needs various forms of alternative energy. But if the solar panel is manufactured at high temperatures using hazardous materials, it still needs additional green chemistry innovation. New and better technologies to purify and desalinate water are important sustainable chemistry technologies, but if the manufacturing processes of these purification systems themselves involve hazardous materials, they still need green chemistry improvements.

Industry should be congratulated for the great advances they have made in sustainable chemistry. But if the sustainable chemistry solutions are not based on green chemistry, people in manufacturing and at product end of life risk exposure to the hazardous materials. The potential impacts on human health and the environment are straightforward, but what is often not fully appreciated is the potential financial costs associate with dealing with the presence of the hazardous components. Mitigating risk by controlling and limiting exposure will almost always come at a cost. Every effort to reduce intrinsic hazard through green chemistry will lessen the dependence on exposure mitigation and all the associated costs. It just makes smart business sense.

8. Green Chemistry and Innovation

In 2007 Jim Babcock and I formed the Warner Babcock Institute for Green Chemistry[18]. While I enjoyed being a professor, I felt that I could have more influence on both academia and industry from an independent position.

The Warner Babcock Institute for Green Chemistry (WBI) is a 40,000 sq ft state-of-the-art chemistry invention factory north of Boston that focuses on creating commercially relevant chemistry technologies consistent with the principles of Green Chemistry. Since its creation WBI has partnered with over 100 companies helping to invent solutions to various industrial unmet needs. Since 2010 WBI has filed approximately 160 patent applications across a wide variety of industry sectors including pharmaceuticals, cosmetics and personal care, construction materials, electronics, alternative energy and water technologies. Recent new companies in hair color restoration[1], asphalt pavement rejuvenation[2], ALS drug therapy[3] and a solar energy[4] have been formed around inventions made at the WBI.

Through the years WBI has had only about 20 scientists working in the labs. 160 patent applications in 9 years with 20 scientists is extremely fast and efficient. While the personnel are very talented, I feel that the major cause of our high productivity is the fact that we do green chemistry. By first focusing on the molecular structure and mechanisms that are consistent with the principles of green chemistry, the scientists receive a creativity boost that differentiates them from traditional chemists. By understanding the various national and international regulatory frameworks at the design stage of the inventive process the time to market can be faster than traditional organizations that must make materials and process changes later in the invention cycle. Many companies that collaborate with WBI seek additional consultation on how to bring these efficiencies into their own R&D labs.

In 2014 I was honored to receive the Perkin Medal[19], the highest honor in US industrial chemistry. In 2016 I was named a Lemelson Invention Ambassador[20]. While I was the individual given these awards, I feel that they were recognition of the entire growing green chemistry community.

9. Beyond Benign

When I left UMASS to form the Warner Babcock Institute for Green Chemistry in 2007, I feared that the massive K-12 outreach efforts to the Metropolitan Boston school systems would likely stop. Dr. Amy Cannon[21], then professor in the UMASS Lowell Green Chemistry program decided to leave at the same time to create the nonprofit organization Beyond Benign[22].

Beyond Benign's K-12 curriculum and teacher programs integrate green chemistry and sustainable science principles into the classroom[23]. They have found that there are numerous benefits for student engagement such as increasing student learning in STEM subjects and inspiring the next generation of scientists and citizens to design and choose greener alternative products by helping equip students to be scientifically literate consumers. Beyond Benign develops and offers free open access lesson plans and curricula to help teachers bring green chemistry into their classroom. On their website they offer nearly 200 downloadable modules for elementary school, middle school and high school that illustrate real world industrial examples of green chemistry tied to specific learning objectives.

Beyond Benign's higher education efforts[24] are centered around their "Green Chemistry Commitment" program[25]. They support college and university faculty and students in implementing and sharing best practices in green chemistry. They offer collaborative working groups, a webinar series, and green chemistry and toxicology curriculum that can be integrated into university chemistry programs. There are currently 60 college and university signers of the Green Chemistry Commitment.

10. Comments of H.R. 2051

The authors and sponsors of "The Sustainable Chemistry Research and Development Act of 2019" should be congratulated[26]. This is a timely effort important to maintaining and growing US industrial competitiveness. While the phrase "sustainable chemistry" is used throughout H.R. 2051, it is important to underscore the critical need to see green chemistry as the fundamental differentiating concept. The structural and mechanistic molecular foundations necessary to invent sustainable technologies is green chemistry. In order to have a workforce with the skills and training necessary to achieve these aspirational objectives, a specific focus on green chemistry must be central to the effort.

11. Concluding Thoughts and Recommendations

There are countless organizations and companies who have turned or are turning their attention to sustainability, the circular economy and other inspirational efforts. Every day there is a conference or workshop where retailers and brand owners convene to discuss various aspects of sustainable business models and products. I am often asked to speak at these meetings. I am usually one of the only chemists in present. This is a problem. A product designer who seeks to create a sustainable product must rely on existing materials in the supply chain. No matter how one sews, bolts, glues or welds a product together, if the fundamental building blocks are not sustainable, the product can't be sustainable. The field of green chemistry provides the skills and training for the design of these new materials.

While the United States has historically been the leader in green chemistry, other countries and regions are accelerating their pace of adopting green chemistry specifically, as a part of their sustainability efforts. CEFIC, the chemistry trade association in Europe, asks me to provide periodic “Green and Sustainable Chemistry Boot Camps” for members of the European chemical industry[27]. The German Ministry of Economic Affairs and the Technical University of Berlin have announced plans for the “John Warner Center for Green Chemistry Start-Ups”[28]. Last month I was asked to speak at the European Commission conference on EU Chemicals Policy 2030[29] to discuss ways to support and grow green chemistry efforts. Several European Asian companies and industry groups ask me to present keynote talks on the role of green chemistry in R&D competitiveness.

From the perspectives of both environmental protection and economic development it is urgent that the US find ways to accelerate education, incentivize investment and facilitate more widespread awareness of green chemistry, the molecular science of sustainability.

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