Unintended Consequences

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Many materials in widespread use in our society contain chemicals that have been shown to have negative impacts on human health and the environment. As the sciences of toxicology and epidemiology become further developed, more and more chemicals are being identified as potentially hazardous to ourselves or our ecosphere. When considering the entire manufacturing process of any specific product of commerce and tracing the assembly and synthesis of each component back to its natural resource (petroleum, ore, plant, etc.), it is likely that most materials involve the use of a hazardous material. Hazards might come in the form of a volatile solvent used in a coating; a reagent or chemical intermediate in the manufacturing process might be toxic. This fact that hazardous materials are being used is inescapable. The question that needs to be explored is, "Why?" Why do we have toxic materials in our society?

Before we address this question directly, it is useful to understand the process by which a new product arrives in the marketplace. A number of steps are involved; products can be seen as assemblies of "functional mechanisms" such as adhesives, pigments, electronics, etc. Engineers and product designers pick and choose from a number of alternatives, a combination of functional mechanisms, to create the final product (cellphones, pens, watches, etc.). These mechanisms are designed and created by chemists and materials scientists who are doing fundamental, or basic, research. A chemist working in the laboratory might be interested in creating a material with some specific characteristic. For example, maybe the scientist is seeking a material that conducts electricity when light is shined on it, or a material that becomes sticky at a certain temperature; or perhaps he or she seeks a material that changes color when it gets wet. While chemists might have a certain type of ultimate product in mind as they create their materials, they are more likely interested in the functional mechanism itself, for a wide variety of possible applications.

So, basic researchers create "functional mechanisms" from chemicals and simple materials. People in applied research and development then combine these mechanisms into devices or products. And then manufacturers figure out a way to make a large number of the devices.

Manufacturers are often aware of the various environmental regulations that govern their respective industries. They will seek out devices and processes that comply with these laws and regulations. When hazardous materials are found to be necessary in a manufacturing process, the manufacturers are required to incorporate technologies that will limit or eliminate the exposure to workers or consumers. The people involved in applied research and development will do their best to create products that are free from hazardous materials, but the sad reality is that sometimes there are no nontoxic alternatives: it is not their skill set to invent these "functional mechanisms." They can only choose from what the chemists and basic researchers give them.

Why do we have toxic materials in our society? One possible reason is that chemists do not know how to make nontoxic materials. This might seem shocking to someone outside the field. Four years of undergraduate education, followed by at least four more years of graduate education, is required for a person to obtain a doctorate in chemistry. Yet, despite this quantity of education, it is unlikely that this person will ever have a single course in toxicology. Mechanisms of environmental fate and transport are unlikely to ever be covered in any class that a chemist takes. And except for the mandated laboratory safety lectures that chemists are given, knowledge of environmental laws and policies remains absent from most chemists' education. How can we ask chemists to create safe materials if they are never taught how?

This is not a condemnation of the chemical education system. The quantity of knowledge that a chemist must master is enormous, and the chemistry educational system works extremely well. Our economy is based on the successes of this system. The wonderful developments in medicine, energy, transportation and agriculture are all direct consequences of the rigorous training we give to our scientists. But just because a system is already excellent, does not mean that it cannot be better.

I titled this piece "unintended consequences" for a few reasons. I do not believe any chemist intentionally creates a hazardous material. But the level of the science today does not provide enough options to avoid unintended consequences. Green Chemistry seeks to fill this gap in knowledge. Green Chemistry asks basic researchers at the very beginning of a design process to consider and understand the toxicological and environmental impacts of their various choices. We have a lot of work to do. It is going to take years, perhaps generations, for us to be able to fully integrate the principles of Green Chemistry into our educational systems. However, it is happening. The twelve principles of Green Chemistry are being discussed in industry and academia more and more.

The Twelve Principles of Green Chemistry [from <u>Green Chemistry: Theory and Practice</u>, by Paul Anastas and John Warner, Oxford University Press 1998]

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 auxiliaries 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 fro 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 of feedstock should be renewable rather than depleting whenever technically and economically practical.
8. **Reduce Derivatives:** Unnecessary derivatization (blocking groups, 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 he 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:** Substances 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.

But there is another perhaps even graver potential unintended consequence. With all the information available about hazardous materials and their effects on human health and the environment, who would ever want to be a synthetic chemist? And if all ethically minded students in chemistry choose careers in monitoring and measuring the effects of materials in our society, who will invent the much needed replacements? We must be careful in our efforts to alert consumers of the hazards and risks associated with toxic materials, so that we do not scare away our next generation of chemists: we need synthetic chemists to invent safer products. But now, more than ever, we need a new set of eyes and ideas on the invention process. If Green Chemistry is allowed to grow throughout our curriculum, I believe that armies of students will rise to the challenge and work to invent a safer future. But if we are not careful, if we drive students away from these pursuits, then we will have no one left to solve these problems, and that could be the worst unintended consequence of all.