Making Safer Chemicals

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The physical and chemical sciences have developed largely independent of the environmental and health sciences. The enormous scientific strides of the nineteenth and twentieth centuries in metallurgy, ceramics, inorganic and organic chemistry and polymers developed our capacities to identify, test, characterize, process and synthesize chemicals with a wide range of commercial applications. The result has been a plethora of structural and functional materials from which hundreds of thousands of products have been made. These products have extended our lives, eased our work, secured our homes, created our wealth, and enriched our lives.

However, as newer, cheaper and more versatile chemicals have emerged from the laboratories many of them have turned out to be toxic, dangerous or threatening to ecological processes. The hazardous characteristics of these new chemicals were seldom recognized or intended. The organic solvents were not designed to be carcinogenic. The refrigerant gases were not intended to damage the upper atmospheric ozone layer. The synthetic plasticizers were not expected to disrupt hormonal systems. Because knowledge from the emerging fields of toxicology, pharmacology and ecology was not integrated into the physical and chemical sciences that generated innovations in chemistry the hazards of new chemicals has seldom been factored into their design processes.

Instead of trying to create a more comprehensive science for generating highly functional, inexpensive and safe chemicals, the emerging knowledge about the hazards of chemicals was used to construct a vast array of professional guidelines and government public health and environmental regulations. Professional associations wrote voluntary standards and drafted guidance manuals for proper handling of hazardous chemicals. Federal and state agencies were established to regulate toxic chemicals in foods, deadly chemicals used in agriculture, toxic chemicals in drinking water, hazardous chemicals in workplaces, dangerous chemicals in products, and polluting chemicals in industrial emissions and wastes.[1]

The conventional approach for establishing these regulations has focused on the perceived dangers of chemicals and the likelihood of human or environmental exposures. Government agencies employ scientific tests and risk determining protocols to assess the dangers associated with exposure to chemicals identified by scientific or public concern. Once exposure to a substance is demonstrated to result in unacceptable levels of harmfulness, agency professionals draft regulations to restrict or condition the use of those substances. This represents a Aproblem-focused@ approach to chemicals management.

This approach has positive features. It tends to focuses on substances of high public concern. It directs scientific attention to a limited number of potential subjects. It seeks to set guidelines for chemicals use and exposure. However, relying on this problem-based approach alone offers an inefficient procedure for achieving a sustainable chemicals future. We certainly need the resources of science to better our collective understanding of the intricacies of chemical processes and the mysteries of biochemical interactions. However expanding knowledge about the behavior and effects of chemicals in the environment and within human bodies is only the first step to achieving a future of safer and more effective chemicals.

We need a parallel approach that focuses less on the characterization of problems and more on the development of solutions. Such a Asolution-focused@ approach would eagerly accept the large accumulation of scientific understanding as a basis for designing chemicals that are safer, cleaner, and more environmentally compatible. Solution seeking approaches to chemical and material development would involve designing chemicals that are not only high performance and cost effective, but also biologically safe and ecologically sustainable.

Seeking Safer Chemistries

A solution-focused approach to chemicals development and production will not come easily. The transition to safer and more sustainable chemicals requires a significant re-direction of the chemical industry and a re-evaluation of its products. Future generations will continue to need chemicals and the industrial transformation of chemicals to meet human needs will continue to require ingenuity and enterprise. However, the types of chemicals and how they are used needs to be reconsidered. Fossil fuels will need to play a much smaller role and wastes from production and consumption will need to be managed and recycled in ways that conserve materials and protect the environment. This transition will require a new mission for the industryBa mission that promotes human health and environmental quality as seriously as the market promotes economic efficiency and product effectiveness.

The foundations for this development are already being laid. Leading firms in the industry and thoughtful government leaders are exploring new goals and new directions for safer chemicals. Some of the most progressive chemical manufacturing and processing firms have established corporate sustainability policies and many of these firms publish reports on the chemicals they use and the chemicals they avoid. Research on new chemicals, new routes of chemical synthesis, new feedstocks, and new chemical services have begun to pay off with cleaner production systems, reduced energy consumption and products that are more easily recycled or biologically disposed. The chemistry and chemical engineering fields have responded with new professional statements, conferences that explore sustainable directions, and educational curricula and texts that integrate environmental considerations into conventional education from the primary schools to graduate training.[2]

In developing safer and more sustainable chemicals several avenues are emerging. One approach involves assembling a list of all of those chemicals characterized by high levels of some type of undesirable hazard or unwanted toxicity and substance-by-substance subtracting undesirable chemicals from the larger list of commonly used chemicals. We can call this Asafer chemistry@ because it works incrementally to avoid substances that are less safe. A second approach involves reviewing the large body of research and studies in toxicology and pharmacology for guiding principles that are known to lead to toxicity and potential hazards and use these as design criteria for designing chemicals less likely to be dangerous. This is similar to the processes now used in Agreen chemistry@ for designing chemicals that are safer and cleaner. A third approach involves identifying those chemicals commonly employed in natural systems to support life and to study the processes by which organisms make materials and draw from these lessons design criteria for developing chemicals. This could be called Aecological chemistry@ because it is based on knowledge gained by studying natural systems.

Approach One:
Avoiding Dangerous Chemicals (Safer Chemistry)

Safer chemistry means designing substances that avoid chemicals commonly recognized as dangerous. In its most simple form this involves avoiding chemicals that are banned by governments or included on lists of dangerous chemicals. Such lists are not difficult to find. Many government agencies have compiled lists of dangerous chemicals. There are also lists published by professional associations and lists of substances to avoid, often called Ablack lists@, drawn up by manufacturing or retail firms.

Some national governments, particularly, in industrialized counties, have banned certain dangerous chemicals. Environmental or health agencies in these governments have used their regulatory powers to phase out or prohibit the manufacture or use of hazardous chemicals such as various pesticides, organo-metals, or halogenated compounds. In 1991, the Swedish government published a list of eight chemicals and chemical groups that it then proceeded to attempt to Asunset@. These included methylene chloride, trichloroethylene, lead, organo-tin compounds, chlorinated paraffins, phthalates, nonylphenolethoxylates and brominated flame retardants.[3] The U.S. Environmental Protection Agency has used its authority under the Toxics Substances Control Act to phase out the use of a small number of industrial chemicals and the federal pesticide laws to prohibit the use of a larger number of insecticides and herbicides. The United Nations publishes an *International Registry of Potentially Toxics Chemicals* that lists over 600 substances that have been banned or severely restricted by some national governments. Recently, the Stockholm Convention on the Persistent Organic Pollutants has targeted twelve organic chemicals for international phase out. The European Union has passed a directive prohibiting the use of lead, mercury, cadmium, hexavalent chromium, and brominated flame retardants in electronic products.

Some European governments publish lists of dangerous chemicals that, while not prohibited, should be avoided. The Swedish government has developed a hierarchy of lists that range from a short list of substances that are to be phased out of use (see Table 1) to a longer list of substances that should be voluntarily avoided. The Swedish National Chemical Inspectorate, KEMI, publishes an AObservation List@ of some 200 chemicals that should be avoided where possible.

Table 1. Partial Swedish List of Restricted Chemical Substances	
Arsenic	Asbestos
Benzene	Benzidine
Bis(chloromethyl) ether	Cadmium
Carbon tetrachloride	Chlorofluorocarbons
Chromium	Dichloromethane
Ethylene glycol	Formaldehyde
Lead	Mercury
Nonylphenolethoxylates	Polychlorinated biphenyls
Pentachlorophenol	Phthalates
Tetrachloroethane	Trichloroethylene

Source: Swedish National Chemicals Inspectorate, *List of Restricted Chemical Substances in Sweden*, Solna, Sweden, November, 1995

The U.S. Environmental Protection Agency (U.S. EPA) lists over 600 substances in its Toxics Release Inventory which some businesses use as a list of chemicals to avoid. Because the agency=s New Chemicals Program must annually review hundreds of new chemicals for possible market entry, the agency has developed a set of procedures for identifying dangerous tendencies. Beginning in 1987 the U.S. EPA began to develop categories of chemicals based on those properties likely to be dangerous. Using the techniques of structure-activity analysis, the agency=s first category was Aacrylates and metacrylates@. Today, there are 45 chemical categories and the Chemical Categories List is generally regarded as identifying those substances least likely to be safe.[4]

Governments and international agencies also publish lists of known and suspected human carcinogens, lists of recognized reproductive hazards, lists of neurotoxins, lists of allergens, lists of endocrine disrupting chemicals and lists of substances known to have negative effects on plants, fish or wildlife. Some particularly bioactive substances appear on several of these lists. Table 2 provides samples of these lists.

Table 2: List of Toxic Substances by Effect				
Substance	Carcinogen	Reporductive Toxin	Neurotoxin	Mutagen/ Teratagen
Acrylonitrile	Probable	Yes		
Arsenic	Known	Yes	Yes	Yes
Asbestos	Known			
Benzene	Known	Yes	Yes	
Benzidine	Known			
Beryllium	Known			
Cadmium	Probable	Yes		Yes
Chromium (+6)	Known	Yes		
Ethylene oxide	Probable	Yes	Yes	Yes
Formaldehyde	Probable	Yes		
Hexane		Yes	Yes	
Lead	Lead acetate	Yes	Yes	Yes
Methyl Mercury		Yes	Yes	Yes
Nickel	Known	Yes	Yes	
Perchloroethylene	Probable			
Polychlorinated biphenyl	Probable	Yes		Yes
Trichloroethylene	Possible	Yes		
Styrene	Possible	Yes		
Vinyl chloride	Known	Yes		

Source: Curtis D. Klaasesen, ed.,, *Casarett and Doull=s Toxicology: The Basic Sciences of Poison*, 5th ed., New York: McGraw-Hill, 1996

Some large manufacturing corporations and retail firms also draw up lists of substances to avoid. Daimler Chrysler, Volvo, Cannon, Sony, and Ben and Jerry=s (ice cream) are all firms that maintain lists of chemicals to avoid in their manufacturing processes. Retailers like Boots and the Body Shop in the United Kingdom also use substance avoidance lists in negotiating with suppliers.

Once such avoidance lists have been accepted as guidance, a practicing chemical engineer needs only to conduct a review of existing chemical processes and identify the steps which need to be re-designed in order to eliminate the listed chemicals. Likewise, the synthetic chemist designing a new substance or synthetic process needs only to consult the lists to develop chemistries that avoid the use of the listed chemicals.

This is not unusual. During the 1980s the United Nations negotiated an international treaty to protect the upper ozone layer. This treaty resulted in the Montreal Protocol that required the phase out of a series of ozone-depleting chlorinated and fluorinated compounds. In response industrial chemists and process managers found substitutes that changed the chemistries of refrigeration, foam blowing and degreasing. The state pollution programs in the United States have assisted hundreds of firms in finding safer chemicals to substitute for highly volatile pollutants. For over a decade the Massachusetts Toxics Use Reduction Program has helped manufacturing firms find safer substitutes for some 190 chemicals that are included on the state list of toxic and hazardous chemicals.

Technically, there are many examples of the search for safer chemistries. Substituting aqueous and semi-aqueous (terpines and alchohols) solvents for chlorinated solvents in industrial parts cleaning and degreasing provides a common example. Converting from mineral-based inks to soy-based inks offers an example that swept the newspaper business during the 1980s and 1990s. During this same period many large mills in the pulp and paper industry moved from hazardous chlorine to more benign chlorine dioxide and peroxide for bleaching and delignification. Many conventional hydrocarbon-based paints and coatings have been reformulated into water-based mixtures that have eliminated ingredients such as toluene, methyl ethyl ketone, formaldehyde, and various isocyanates.[5]

Safer chemistry does not mean safe chemicals. For years, carbon tetrachloride was used as an industrial degreasing agent. During the 1940s evidence began to mount of the toxic effects of carbon tetrachloride on the liver and kidneys and it was gradually replaced by trichloroethylene and perchloroethylene in degreasing. However, by the 1980s these solvents were listed as possible carcinogens.   In some applications glycol ethers were substituted for the chlorinated solvents to avoid a suspected carcinogen, but ethylene glycol was found to be a reproductive toxin. Today, ethylene glycol is often replaced by propylene glycol, however, this too may someday need to be replaced.

Safer chemistry provides an effective strategy on a very practical basis, but it is an incremental strategy that promotes minor innovations in a kind of step-wise evolutionary process. Step-by-step safer chemicals replace one another in a long march away from recognized hazards. However, the transition to more sustainable chemistries could be advanced more rapidly by adopting a less incremental and more discontinuous process that seeks environmental compatibility as a direct, self-conscious and normative goal.

Approach Two:
Designing Chemicals based on Health and Environmental Sciences   (Green Chemistry)

The state of chemistry, biology, and physics and knowledge about physiology and toxicology has advanced enormously over the past half century. We know far more about what makes chemicals toxic and hazardous and how to make them safer than we once did. For years chemists and chemical engineers have focused their research on questions of functional performance, processing efficiency, and cost with little attention to the health or environmental effects of their chemicals. However, the increasing public criticism of chemists and chemistry during the 1980s led some chemists to argue that there is adequate knowledge for designing chemical and chemical processes that pose less risk to human health and the environment. Over this last decade, some in the field began to fashion a more environmentally-benign approach to chemistry.[6]

The idea of using existing knowledge from the health and environmental sciences to design more environmentally-friendly chemicals and chemical processes has opened a rapidly developing new specialty in chemistry often referred to as environmentally-benign chemical synthesis, or Agreen chemistry@. Green chemistry does not focus on incremental substance substitutions; instead, green chemistry focuses on developing alternative chemistries that can be introduced throughout the entire process of the chemical manufacturing. Paul Anastas and John Warner, two of the founders of the field of green chemistry, have defined the term green chemistry to mean "the utilization of a set of principles that reduces or eliminates the use or generation of hazardous substances in the design, manufacture and application of chemical products". [7]

In a seminal book on green chemistry, Anastas and Warner have drawn up a list of twelve principles that can be used to identify and guide green chemistry initiatives in making more environmentally-benign substances. Table 3 lists the twelve principles.

Table 3: Twelve Principles of Green Chemistry
1. It is better to prevent waste than to treat or clean up waste after it is formed.
2. Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.
3. Wherever practicable, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment.
4. Chemical products should be designed to preserve efficacy of function while reducing toxicity.
5. The use of auxiliary substances (e.g. solvents, separation agents, etc.) should be made unnecessary wherever possible and innocuous when used.
6. 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. A raw material of feedstock should be renewable rather than depleting wherever technically and economically practicable.
8. Unnecessary derivatization (blocking group, protection/deprotection, temporary modification of physical/chemical processes) should be avoided whenever possible.
9. Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.
10. Chemical products should be designed so that at the end of their function they do not persist in the environment and break down into innocuous degradation products.
11. 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. Substances and the form of a substance used in a chemical process should be chosen so as to minimize the potential for chemical accidents, including releases, explosions, and fires.
Source: Paul T. Anastas and John C. Warner, *Green Chemistry: Theory and Practice*; Oxford University Press; New York, 1998.

It is important to note that a green chemistry approach, like the previous approach, does not start with a focus on exposure or risk. Green chemistry is directed at the factors that make chemical processes toxic or hazardous. Through a careful consideration of the properties of chemicals that make them toxic or hazardous, it is possible to Adesign out@ those properties and, thereby, reduce or eliminate the hazard. Anastas and a colleague at the U.S. EPA, Tracey Williamson, make this goal clear when they conclude, "(g)reen chemistry seeks to reduce or eliminate the risk associated with chemical activity by reducing or eliminating the hazard side of the risk equation thereby obviating the need for exposure controls and, more importantly, preventing environmental incidents from ever occurring through accident. If a substance poses no significant hazard, then it cannot pose a significant risk....."[8]

Green chemistry fosters research on alternative feedstocks and intermeadiaies, environmentally benign solvents, reagents, and catalysts, aqueous processing, and safer and more readily recyclable chemical products. This involves preferring renewable (bio-based) feedstocks over non-renewable (petroleum-based) sources and seeking starting materials that demonstrate the least hazardous properties (e. g. toxicity, flammability, accident potential, eco-system incompatibility, ozone depleting potential, etc.). Employing polysaccharides as feedstocks for polymers is an example of a renewable and non-toxic material for beginning a synthesis pathway. Likewise, glucose can be used as a raw material rather than benzene in the production of hydroquinone, catechol, and adipic acid, all of which are important intermediaries in the production of commodity chemicals. Indeed, relatively non-toxic silicon has been suggested as a useful replacement for carbon as a starting base for the synthesis of some organic chemicals.[9]

Atom economy is a simple way of describing improvements in yield- -getting the maximum amount of chemical product out of each reaction. This involves both selecting the most atom efficient reactions as well as developing new, more atom economical ways of carrying out current reactions that often minimize the number of process steps, thereby reducing energy inputs and waste generation.

Additional research focuses on alternative reagents and catalysts. This involves identifying catalysts that function in chemical transformations with minimal environmental harm (e. g. minimizes energy inputs, maximizes yield, minimizes waste outputs, generates the least occupational exposure and the least accident potential). For instance, addition reactions are preferred over subtraction reactions, because they incorporate much of the starting materials and are less likely to produce large amounts of waste. Alternatives to heavy-metal catalysts are sought, because the common metal catalysts are so often extremely toxic. The use of liquid oxidation reactors replaces metal oxide catalysts with pure oxygen and permits lower temperature and pressure reactions with higher selectivity and no metal contaminated wastes. New catalysis techniques that rely on enzymes, microwaves, ultrasound or visible light obviate the need for harsh chemical catalysts.[10]

Organic solvents with significant health and environmental impacts are conventionally used as carriers in chemical reactions. Investigations on alternative solvents have demonstrated the potentially wide applications of aqueous chemistries, ionic liquids, immobilized solvents, and supercritical fluids. Water has been shown to be an effective solvent in some chemical reactions such as free radical bromination. Supercritical fluids which are typically gases (CO_2) liquified under pressure are already commonly used in coffee decafination and hops extraction.

Supercritical CO_2 can be used as a replacement for organic solvents in surface preparations, in cleaning, and in polymerization reactions and surfactant production. Future work may involve solventless or "neat" reactions such as molten-state reactions, dry grind reactions, plasma-supported reactions, or solid materials-based reactions that use clay or zeolites as carriers.[11]

Several firms within the pharmaceutical industry, such a Merck, Pfizer, Bayer, and GlaxoSmithKline, have taken leadership positions in promoting green chemistry. Because drug development is so research intensive and the health care industry is so sensitive to health objectives these firms have found competitive benefits in promoting their green chemistry initiatives.[12]

The Office of Pollution Prevention and Toxics at the U.S. EPA has several years of experience in trying to promote green chemistry. For instance, the New Chemicals program has developed a computer-based program called the Synthetic Method Assessment for Reduction Technique that helps chemical companies to assess, in advance, the pollution prevention opportunities of new chemistries and a Green Chemistry Expert System that helps companies to identify and design more environmentally benign chemicals.

These green chemistry initiatives have received a substantial boost by the federal government=s sponsorship of an annual presidential awards ceremony for the nation=s best examples of green chemistry applications. Over the past several years, this awards program has recognized Bayer=s environmentally friendly synthesis of biodegradable chelating agents, PPG Industry=s use of yttrium as a substitute for lead in cationic electro-coatings, and Rohm and Hass=s design of an environmentally safe marine antifouling coating to replace tributyltin oxides.[13]

Green chemistry goes a long way to promoting avenues for more sustainable chemistry. Avoiding toxic and hazardous substances, optimizing yields, avoiding wastes and minimizes energy consumption generates a broad set of objectives for encouraging innovation and corporate leadership. However, green chemistry stays within the conventional structures of the current chemical industry. An even broader challenge can be envisioned by seeking to follow the paths evolved by nature in the development of chemicals.

Approach Three:
Modeling Chemistry after Natural Systems (Ecological Chemistry)

The third approach is based on biology, physiology, and ecology and focuses on developing chemicals that are inherently benign because they respect the biological defenses of living organisms and because they are ecologically compatible and degrade naturally under ambient environmental conditions. This involves digestible substances that are safely metabolized and biodegradable and readily compostable materials that fit comfortably into ecological nutrient streams..

While chemists and material scientists have long studied natural systems to discover the structural properties and synthetic processes in the environment, the lessons have focused narrowly on function and efficiency and neglected the health and environmental aspects. Many early polymers were designed as derivatives of natural polymeric compounds and, today, many pharmaceuticals are based on compounds found in living plants and animals. However, the emergence of a specialty of field-based research, currently called Abiomimetics@ or Abiomimicry@ has drawn together a group of natural scientists who study nature to find environmentally compatible processes. These explorations include studies of how organisms make and use materials to compose physiological structures, communication systems, habitats and tools.[14]

A starting point for this research is feedstocks. The production of chemicals from biomass is currently receiving renewed attention. This ranges from the production of biopolymers to bio-based cleaners and solvents.[15] Before the synthetic chemicals revolution and the advent of petrochemicals chemicals were largely derived from plant matter. Still today biomass provides the basis for nearly 6 percent of pigments, 35 percent of surfactants and 40 percent of adhesives. Soy-based inks are the standard for color reproduction in newspapers. In 2000, the U.S. Congress passed a Biomass Research and Development Act to provide new federal support for research on biobased fuels and chemical products. Primarily viewed as a means of expanding markets for agricultural products and reducing export dependence, this initiative, nonetheless, has spurred the search for Anew uses@ of biobased chemicals.[16]

However, ecological approaches to chemistry go well beyond agricultural feedstocks. A brief examination of natural processes reveals natural processes for making thousands of different chemicals and material Aproducts@ ranging from pliable polymers, rigid membranes and crack-resistant ceramics to surface coatings, adhesives, gels, lubricants, inks, dyes, and disinfectants. There are natural processes for making energy conductors, insulators, data processors, information storage, and information translators. Natural processes make proteins, fats, carbohydrates, amino acids and the vitamins and nutrients necessary for life. Considering how organisms make tough, polymeric materials like skin, hair, or shells reveals the wide variety of natural chemistries. Indeed, for most any synthetic chemical product there is a similar natural product made through relatively benign and renewable processes. Unlike current petrochemical based processes, natural processes for producing chemicals are often quite sophisticated, occur under ambient conditions, require small amounts of energy, generate high yields, and produce limited wastes that are easily consumed by other natural processes.

Ecological chemistry involves studying nature for materials and processes that are safe and ecologically sound. This could begin with a list of those substances that make up the human body.[17] Table 4 lists the essential elements in human anatomy by volume.

Table 4. Essential Elements in the Human Body

Element	Fraction of Total Body Mass

Oxygen	61%
Carbon	23%
Hydrogen	10%
Nitrogen	2.6%
Calcium	1.4%
Phosphorus	1.1%
Sulfur	0.2%
Potassium	0.2%
Sodium	0.14%

Source: John Emsley, *Nature=s Building Blocks An A-Z Guide to the Elements*, New York: Oxford University Press, 2001

Add to this list those compounds and chemical structures that make up common human foods. People have been exposed to the carbohydrates, starches, proteins, fats, minerals and vitamins that make up the human diet for centuries. In many ways humans and their diets have co-evolved to sustain one another. Indeed, the U.S. Federal Food and Drug Administration maintains a list of food additives that are commonly considered safe. This list contains the names of hundreds of substances that are Agenerally regarded as safe (GRAS)@ by the agency because there is a long safe history of common uses in foods or a strong weight of published scientific evidence suggesting that they are without negative human health effects. Because this list contains a broad array of organic and inorganic chemicals, it provides a useful list of potential chemicals available for industrial production that are to the best of our knowledge compatible with human and biological health.

The human food source is rich in organics and the processes by which seeds, grains, legumes and other food plants develop could provide a host of lessons on chemical processes that are likely to be compatible with health and well being. This is not the same as saying that all biomass produced chemicals are likely to be safe. Ecological chemistry focuses on both the chemical product and its production process. The recent scientific and policy interests in bio-based processing and chemistries based on biomass offer exciting opportunities, but too often careful attention to the production processes is neglected. Studying natural production processes is the key to ecological chemistry and to date this is fairly un-chartered territory.

Ecological chemistry involves taking what biologists, botanists and ecologists study to generate templates and procedures for the development of more environmentally-friendly chemistries. Starting with processes that are compatible with human cells, some examples of such a list would include:

Table 5. Rules for Ecological Chemistry

X	design chemicals to be less likely to damage a living organ or cell,
X	design chemicals to be less likely to reach a target organ or cell or to be stored there once it has been absorbed into an organism,
X	design the physical properties of a chemical to be less likely to be absorbed into an organism,
X	design chemicals that are likely to rapidly degrade in the environment or be converted to nutrients in an organism,, and
X	select production and use processes that occur at normal temperatures and pressures and minimize water and energy use.

Source: Kenneth Geiser, *Materials Matter, Towards a Sustainable Materials Policy,* Cambridge, MA: MIT Press, 2001.

Inherently Safe Chemicals. Biological systems rely on a relatively small number of the chemicals in the periodic table. Healthy, living organisms are quite selective about the chemicals they consume as building blocks and fuel sources. They clearly avoid chemicals likely to damage DNA or interfere with the functioning of RNA. Proteins and enzymes perform a wide range of chemical functions in manufacturing structures, surfaces and barriers and they do so in quite controlled procedures. The self-assembly processes of constructing templated polymer structures is an additive process that generates little or no waste. Where reactions do occur chemicals are "un-zipped" into reactive forms only for the time needed to carry out the reaction and the wastes are typically re-bonded (blocked) to a less reactive state.

Non-bioavaiable Chemicals. If organisms create selectively impermeable membranes to shield vital functions from exogenous chemicals, then chemicals are selected that respect those barriers. Compounds that are composed of large, dissociated, non-lipophilic molecules are less likely to cross the cellular membranes of organisms. Water soluble chemicals, for example, are less likely to pass through cell membranes than lipid soluble chemicals. Large molecule polymers are less likely to be absorbed than small molecule polymers. Chemicals that can not penetrate the membranes of cells or fat molecules are less likely to be stored and accumulate in organic tissue.

Physically Benign Chemicals. The physical properties of a chemical affect the possibility that it will be easily transported in the environment of readily absorbed into an organism. For instance, materials in fine powder form are likely to be transported in the air and easily inhaled. The same material in pellet, slurry or solid mass form is less likely to be transported on air currents, dispersed onto food or water supplies, or inhaled into respiratory systems. Materials that easily volatilize are more readily transported and inhaled as vapors or gases, than materials with lower molecule weights. Where a fine dust or volatile state is required, a material could be converted to that state for the minimum time necessary before returning to a less dissipative state.

Biodegradable Chemicals. Natural processes display complex processes that assure that structural and barrier materials are durable (resist degradation) for certain time periods, but that at later times are easily biodegraded under natural conditions or readily metabolized inside organisms. Snake skins that are periodically molted, provide a graphic example. It is often possible to place functional groups into the molecular structure of a chemical such that prolonged sunlight or microorganisms can degrade the substance with relative ease. The biodegradable polymers based on starch and other carbohydrates provide examples and a wealth of lessons.

Ambient Condition Processing. The ambient conditions at the surface of the planet are quite enough for most natural chemical processes. Chemicals that are produced and used at ambient temperature and pressure are less likely to dissipate, volatilize, or leak. Processing chemicals at ambient conditions also reduces the likelihood of exothermic reactions such as explosions and fires. Biosynthesized chemicals such as carbohydrates and alcohols provide a good example. Such chemicals are also more likely to require less water and energy use over their full life cycle and, thus, generate less environmental pollution or organism exposure in ancillary processes.

Basing chemistry on currently available natural models may appear to limit creativity and innovation. However, this need not be the case. Natural processes are often highly sophisticated and elegant in ways the conventional synthetic processes avoid because it is so much easier to simply force reactions with intense amounts of heat, pressure and harsh chemistries. Natural processes are also likely to offer superior qualities in terms of efficiency and waste minimization or in terms of waste generation that has readily available uses within ecological systems. Learning how to make chemicals with the cleverness of nature can open up engaging new avenues for creative chemistry.

Ecological chemistry approaches may yield many solutions that are similar to results of green chemistry approaches. However rather than go through the literature of toxicology and pharmacology to create design criteria, ecological approaches start with how nature makes chemicals and then tries to copy or mimic those procedures. Both green chemistry and ecological chemistry offer truly innovative approaches to making safer chemicals and both provide challenging directions for developing a more sustainable chemical industry.

Safer Chemicals for the Future

Securing a productive, safe and sustainable society is a laudable goal that most would accept. Chemicals and the chemical industry have a large role to play. The planet has limited resources, however, our capacity to manipulate those resources through our increasing knowledge of the physical sciences promises a wealth of products and services. Making the results safe and enduring presents a significant challenge. We can continue to rely on a problem-based approach that addresses the hazards of chemicals only after they have been developed, manufactured and released to the environment. Progress on this approach will be slow and costly.

Instead, we could use our ever increasing ecological and physiological knowledge to shape and direct our search for inexpensive and productive chemistries. This will require new goals for the discipline of chemistry and new directions for the chemical industry. Significant efforts to redesign educational programs in chemistry, biology, biochemistry, and chemical engineering will be needed. Graduates in the chemistry fields of the future will need to be well prepared in the science of chemicals and also well versed in understanding environmental health. While, chemists need not become toxicologists, pharmacologists or ecologists, they should be able to engage these fields with confidence and appreciation.

We should be expecting a lot from the chemicals of the future. They need to continue to provide low cost and high quality performance. However, they also need to be safe as well as functional and sustainable as well as practical. This paper has attempted to lay out several avenues for making such chemicals. Most of these initiatives are still in early stages. Much more work is needed here, but the successes so far are impressive and promising.

NOTES

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1. For more of this history see Kenneth Geiser, *Materials Matter: Towards a Sustainable Materials Policy*, Cambridge, MA: MIT Press, 2001.

2. David T. Allen and Kirsten Sinclair Rosselot, *Pollution Prevention for Chemical Processes*, New York: Wiley, 1997; and David T. Allen and David R. Shonnard, *Green Engineering: Environmentally Conscious Design of Chemical Processes*, Upper Saddle River, N.J.: Prentice Hall, 2002.

3. Swedish National Chemicals Inspectorate (KEMI), *Risk Reduction of Chemicals: A Government Commission Report*, Solna, Sweden, 1991.

4.The most recent AChemical Category for Persistent, Bioaccumulative, and Toxic Substances@ establishes those properties not desirable in the development of new chemicals.

5.For further examples see Allen and Rosselot, Wiley, 1997.

6.For a extensive review see J. A. Cano-Ruiz and G. J. McRae, AEnvironmentally Conscious Chemical Process Desugn@, *Annual Review of Energy and Environment*, 23, 1998, pp. 499-536.

7.Paul T. Anastas and John C. Warner, *Green Chemistry: Theory and Practice*, New York: Oxford University Press, 1998, p. 11 and p. 30.

8.Paul T. Anastas and Tracy C. Williamson, "Frontiers in Green Chemistry", in Paul T. Anastas and Tracy C. Williamson, eds., *Green Chemistry: Frontiers in Benign Chemical Syntheses and Processes*, New York: Oxford University Press, 1998, p. 10.

9.Scott Sieburth, "Isosteric Replacement of Carbon with Silicon in the Design of Safer Chemicals", in Stephen C. DeVito and Roger L.Garrett, eds., *Designing Safer Chemicals: Green*

Chemistry for Pollution Prevention, Washington, D.C.: American Chemical Society, 1996, pp. 74-83.

10. See G. Centi, P. Ciabelli, S. Perathoner and P. Russo, AEnvironmental Catalysts: Trends and Outlook@, *Catalysis Today*, 2691, 2002, PP.1-13.

11. See Jurgen Metzger, AOrganic Reactions without Organic Solvents and Oils and Fats as Renewable Raw Materials for the Chemical Industry@, *Chemosphere*, 43, 2001, pp. 83-87.

12. For a good review of work at GlaxoSmith Kline see Alan Curzons, David Constable, David Mortimer and Virginia Cunningham, ASo You Think Your Process is Green?BUsing Principles of Sustainability to Determine what is`GreenBA Corporate Perspective@, *Green Chemistry*, 3, 2001, pp.1-6.

13.For other examples see the Internet site: www.epa.gov/greenchemistry.

14. Janine M. Benyus has written a non-technical and quite readable review of these investigations in *Biomimicy: Innovation Inspired by Nature*, New York: William Morrow, 1997.

15. See Robert C. Brown, *Biorenewable Resources: Engineering New Products from Agriculture*, Ames, Iowa, Iowa State Press, 2003.

16. About a dozen federal agencies participate in the federal Biobased Products Coordinating Council. For further information go to the Internet site at www.ars.usda.gov/bbcc and see Marvin Duncan, AU.S. Federal Initiatives to Support Biomass Research and Development@, *Journal of Industrial Ecology*, 7:3-4, 2004, pp. 193-201.

17. A chemical by chemical description in abbreviated, but quite readable, form can be found in John Emsley, *Nature=s Building Blocks: An A-Z Guide to the Elements*, New York: Oxford University Press, 2001.