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Skip to main content Mitigating Risk and Hazard Is there difference? Formally, in chemical fields, risk can be defined as a function of hazard and exposure: Risk = f (hazard, exposure) Traditionally, in industry and society, the reduction of risk is achieved through the reduction of exposure. By characterization of hazards (toxicity data) and knowing the effectiveness of the exposure controls ('containing the hazard'), risk can be manipulated or dissipated, especially at the early stages of the chemical chain, when it is easy to identify and measure. However, exposure controls may be not as useful downstream. The farther the hazard is from its source, the less the awareness of the potential hazard. With uncertainties in chronic effects, bio-accumulation, synergistic effects of chemicals, there is an uncertainty in risk mitigation. The Green chemistry approach, in contrast with traditional practice, targets risk reduction through reduction of hazard. This is a safer approach because, if hazard is eliminated in the first place, there is no way risk can increase through any unpredicted spontaneous exposure increase anywhere downstream (Anastas and Warner, 1998). We do not need to go too far to find an example. Let us look, for instance, at the relatively recent chemical accident in Warsaw (Indiana). The Warsaw Chemical Co. plant produces car washing products and stores a number of hazardous chemicals on site. While the plant poses a potential environmental risk, that risk is mitigated by limiting the exposure: chemicals are contained in tanks, which are monitored; second containment is in place; operating equipment is regularly checked by qualified technicians; special personnel is trained to deal with leaks. The facility is also required to have a risk-management plan. The product the company makes is designed to contain only small amounts of hazardous components, which are dissipated in use. All these measures make sure any contact of the dangerous chemical with the environment or humans occurs in a small-scale, controlled manner. This, however, does not eliminate risk itself - it is strictly controlled, but it is still there. When accidental fire caused several explosions at the facility, the tanks containing the hazardous chemicals - mostly methanol - were ruptured, and the hazard was forced out of containment. Chemicals were apparently released to the nearby area and possibly leaked into the nearby lake via storm water stream. The immediate response included the measures such as: evacuation of public from the area, ban for using lake (for fishing or other activities), isolation of the spill and cleanup the affected soil and surfaces. Possibly, also the risk management plan will need revision to make sure that such harm is avoided in the future. In the current situation, all these measures are appropriate, but they are all again - exposure limiting. And, therefore, they are limited in effectiveness. Green chemistry approach calls for minimizing the hazard. Instead of controlling methanol, get rid of it. Use a non-hazardous material instead. If it leaks, there is no hazard. No hazard - no risk. However, this approach clearly requires some expertise and investment from the company. Because the company, even though wanting to be green, wants to stay competitive and profitable, green approach is a technical challenge for product designers. News source: Chemical plant blast injures 8, poses environmental concerns, INDYStar/ Accessed: 2/9/2015. Green Chemistry Control Keys So, what are possible avenues for changing the existing practices towards the minimum-risk alternatives? There are several controls that can be manipulated at different stages of a chemical manufacturing process. Using alternative feedstock or starting materials: Selection of the starting materials has a major effect through the whole synthetic pathway. It determines what hazards will be faced by the workers extracting the substance, shippers transporting the substance, chemists handling the substance. It also predetermines possible future risks from the end-products and wastes. Using more environmentally benign alternative feedstock may improve the environmental profile of the whole process (this links to green chemistry principle #7). One of the examples of this step is choosing between the petroleum feedstock and biological feedstock. Currently, 98% of all organic chemicals in the USA are produced from petroleum. Petroleum refining is extremely energy-consuming (15% of total national energy use) and contains high-pollution oxygenation processes. Agricultural feedstocks can be a great alternative that eliminate much of that hazard. Research has shown that many agricultural products (e.g., corn, soy, molasses) can be transformed via a variety of processes into textile, nylon, etc. (Anastas and Warner, 1998). Using alternative reagents: Reagents are needed to transform the starting molecules into a target substance. Reagents are not necessarily consumed and are often recycled, but can still bear harm to people and environment exposed to the process. At this point, a chemist must balance the criteria of chemical efficiency and availability with potential hazards. This practice taps into green chemistry principles #2, 4, and 5. Using alternative solvents: Solvents are a very common focusing point because a wide range of syntheses are performed in the liquid media. Many of the currently used solvents are volatile organic compounds. Many of those are responsible for air quality problems (smog, etc.) when released to air. While the traditional organic solvents are easily available, well characterized, and regulated, there is a push for alternative systems that are more environmentally benign in the long run – aqueous solvents, ionic liquids, immobilized solvents, supercritical fluids, etc. (Principle #5) The choice of an alternative solvent requires careful and specific analysis, which determines if the new process would be as efficient or as cost-effective. How such trade-offs are resolved is discussed later in this lesson. Changing target product: Chemistry is function oriented – the target chemical is needed to perform a certain function or possess certain properties. This avenue is related to the search of the alternative final product, which may require radical change in the way synthesis is done (Principle #3). Through chemical research, it is possible to identify those parts of a molecule that provide the chemical with a desired function as well as those parts that provide toxicity. Maximizing the former and minimizing the latter is a worthy challenge for chemical design. Process monitoring: Real time measurements (sensing) of process parameters and concentrations sometimes provide valuable information and hints how the process should be tuned to avoid adverse effects or risk (Principle #11). Also, process monitoring may open avenues for making the process more cost-effective. Alternative catalysis: Catalysis bears enormous benefits, not only from the standpoint of technical efficiency. Environmental benefit results from the use of a much smaller amount of reagents in catalyzed reactions, which otherwise would contribute to the waste stream. Using less chemicals is also economically profitable. It should be noted, though, that many classes of catalysis (e.g., heavy metals) are very toxic. Hence, the challenge of alternative catalysis is to develop environmentally benign options (Principle #9). As you can see, most of these measures are oriented towards reducing hazard in the first place. Eliminating, minimizing, or neutralizing toxic components at earlier stages of the process allows for more relaxed exposure control at later stages. Item 5 is more universal, as sensing can help monitor and control both toxicity and exposure at both inlet and outlet of the chemical system. The green chemistry principles are also important as guidance for designing metrics for chemical technology evaluation. Some examples of those metrics are discussed further in section 4.3. Anastas, P. T., Warner, J. Green Chemistry: Theory and Practice; Oxford University Press: London, 1998. This book provides more explanation on the green chemistry principle and desired impacts, overviews the methods to design safer chemicals, and describes a handful of good examples of how the green chemistry principles are implemented in real-life scenarios. This book is not a required reading, but is recommended as a resource for design sustainability assessment of green chemistry projects. It is better to prevent waste than to treat or clean up waste after it has been created. Contributed by Berkeley W. Cue, Jr., Ph.D., BWC Pharma Consulting, LLC. In their publication "Green Chemistry, Theory and Practice" in 1998, Anastas and Warner introduced their 12 principles. My view is the first principle, often referred to as the prevention principle, is the most important and the other principles are the "how to's" to achieve it An often-used measure of waste is the E-factor, described by Roger Sheldon, which relates the weight of waste coproduced to the weight of the desired product. More recently, the ACS Green Chemistry Institute Pharmaceutical Roundtable has favored process mass intensity, which expresses a ratio of the weights of all materials (water, organic solvents, raw materials, reagents, process aids) used to the weight of the active drug ingredient (API) produced. This is an important roundtable focus because of the historically large amount of waste coproduced during drug manufacturing—more than 100 kilos per kilo of API in many cases. However, when companies apply green chemistry principles to the design of the API process, dramatic reductions in waste are often achieved, sometimes as much as ten-fold. So, it is important to extend the impressive results achieved by the ACS GCIPR to all parts of the drug industry, especially the biopharma and generic sectors, as well as to other sectors of the chemical enterprise where synthetic chemistry is used to produce their products. More Resources & Examples: Articles Cited: The E Factor: fifteen years on; R.A. Sheldon; Green Chem. 2007, (9), pp 1273-1283, DOI: 10.1039/B713736MUsing the Right Green Yardstick: Why Process Mass Intensity Is Used in the Pharmaceutical Industry to Drive More Sustainable Processes; Concepcion Jimenez-Gonzalez, Celia S. Ponder, Quirinus B. Broxterman, and Julie B. Manley; Org. Process Res. Dev., 2011, 15 (4), pp 912–917, DOI: 10.1021/op200097d. Synthetic methods should be designed to maximize incorporation of all materials used in the process into the final product. Contributed by Michael Cann, Ph.D., Professor of Chemistry, University of Scranton The second principle of green chemistry can be simply stated as the "atom economy" of a reaction. Atom economy, which was developed by Barry Trost1, asks the question "what atoms of the reactants are incorporated into the final desired product(s) and what atoms are wasted?" Traditionally, the efficiency of a reaction has been measured by calculating the percent yield. Let us assume that the following substitution reaction gives 100% yield. While this is admirable, we can shed more light on the efficiency of a reaction by calculating the "percent atom economy" as follows: Text Version of Reaction: $H_3C\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{—}OH + Na\text{—}Br + H_2SO_4 \longrightarrow H_3C\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{—}Br + NaHSO_4 + H_2O$ % Atom Economy = (FW of atoms utilized/FW of all reactants) X 100 = (137/275) X 100 = 50% The percent atom economy is simply the formula weight of the desired product(s) (compound 4, 137 g/mol) divided by the sum of the formula weights of all the reactants (275 g/mol), which gives 50% in this case. Simply put, even if our percent yield is 100%, only half the mass of the reactants atoms are incorporated in the desired product while the other half is wasted in unwanted by-products. Imagine telling your mom you baked a cake and threw away half the ingredients! Thus chemists must not only strive to achieve maximum percent yield, but also design syntheses that maximize the incorporation of the atoms of the reactants into the desired product. Principle #2 deals with the reactants. However, as those of us who have run a chemical reaction know, we usually use other materials such as solvents and separating agents during a synthesis. These materials usually make up the bulk of the material input, and thus we must also account for the waste that is produced from them. Stay "tuned" as you will see these discussed in subsequent Principles of Green Chemistry. More Resources & Examples: Articles Cited: 1. The Atom Economy-A Search for Synthetic Efficiency; Barry M. Trost; Science 1991, (254), pp 1471-1477. Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment. Contributed by David J. C. Constable, Ph.D., Director, ACS Green Chemistry Institute® When you think about it, this is a two-part principle divided by the first two words, "wherever practicable." Saying those two words implies that it may not be practical or possible to avoid using substances that are toxic, and this is, if you will, the get out of jail card most chemists use to try to avoid applying this principle to their work. Let's face it; chemists use toxic substances all the time because reactive chemicals afford reactions that are kinetically and thermodynamically favorable. And unless—and until—replacement chemicals along with new synthetic protocols are developed, inherently toxic materials will continue to be used. But it's easier to say that it isn't practicable and dispense with any thought about the chemical choices that are made. It's not that adhering to this principle is particularly difficult to do; it's more that chemists are disinterested in doing it. For the synthetic organic chemist, effecting a successful chemical transformation in a new way or with a new molecule or in a new order is what matters. I have heard such arguments, as "all the other stuff in the flask is just there to make the transformation possible so it really doesn't matter," or "you have to be realistic and focus on the science." Saying these things implies that the only science that matters is activating a carbon atom to functionalize it, or adding a ligand to a catalyst, etc., etc. This principle is asking chemists to broaden their definition of what constitutes good science. What many have shown over and over again is that toxicity and the attendant hazard and risk associated with a chemical reaction is directly related to all the other "stuff" in a flask. In fact, the chemistry or chemical transformation in a synthesis generally impacts the overall toxicity profile (and most other measures of sustainability and green) of a product or process the least, except in those cases where we deliberately are producing a molecule that is toxic or biologically active by design. That is certainly the case for many molecules that are synthesized as in the pharmaceutical or agriculture chemical business—the molecules are toxic and/or have other effects on living organisms by design. The chemicals and materials used in effecting chemical transformations matter and chemists need to pay more attention to the choices they make about what goes into the flask. It's easy to discount all the other "stuff" and focus all our energy on the synthetic pathway that delivers the desired product. But when we ignore all the other "stuff," we pay a high price and it's a price we need to stop paying. Occasionally, chemists do produce molecules that have toxic or other hazardous effects, and the next principle will have something to say about designing safer molecules. Chemical products should be designed to preserve efficacy of function while reducing toxicity. Contributed by Nicholas D. Anastas, Ph.D., U.S. Environmental Protection Agency- New England Minimizing toxicity, while simultaneously maintaining function and efficacy, may be one of the most challenging aspects of designing safer products and processes. Achieving this goal requires an understanding of not only chemistry but also of the principles of toxicology and environmental science. Highly reactive chemicals are often used by chemists to manufacture products because they are quite valuable at affecting molecular transformations. However, they are also more likely to react with unintended biological targets, human and ecological, resulting in unwanted adverse effects. Without understanding the fundamental structure hazard relationship, even the most skilled molecular magician enters the challenge lacking a complete toolkit. Mastering the art and science of toxicology requires innovative approaches to chemical characterization that state that hazard is a design flaw and must be addressed at the genesis of molecular design. The intrinsic hazard of elements and molecules is a fundamental chemical property that must be characterized, evaluated and managed as part of a systems-based strategy for chemical design. Now is the ideal time to develop a comprehensive and cooperative effort between toxicologists and chemists, focused on training the next generation of scientists to design safer chemicals in a truly holistic and trans-disciplinary manner through innovative curricular advancements. The field of toxicology is evolving rapidly, incorporating and applying the advancements made in molecular biology to reveal the mechanisms of toxicity. Elucidation of these pathways serve as the starting point for articulating design rules that are required by chemists to guide their choices in a quest to make safer chemicals. We are at the dawn of a new sunrise, poised to illuminate the path forward to a safer, healthier and more sustainable world. More Resources and Examples Anastas, N. Green Toxicology, 2012 in: Green Techniques for Organic Synthesis and Medicinal Chemistry, W. Zhang and B. Cue, eds., J Wiley.Anastas, N.D. and J.C. Warner. 2005. Incorporating Hazard Reduction as a Design Criterion in Green Chemistry, Chem. Health. Safety, March/April, 3-15.Green Chemistry Metrics: Measuring and Monitoring Sustainable Processes, 2009, A. Lapkin and D. Constable eds., J. Wiley.Green Chemistry Education: Changing the Course of Chemistry, 2009, ACS Symposium Series 1011, P.T. Anastas, I. Levy and K.E. Parent, eds. J. WileyDesigning Safer Chemicals, 1996, S. DeVito and R. Garrett eds., ACS Symposium Series 640.US EPA, 2013, Tox21 (accessed 3/3/13) Disclaimer: Although these references are given to provide additional information that may be useful or interesting, EPA is not responsible for, and cannot attest to the accuracy of, the content of these articles. The use of auxiliary substances (e.g., solvents, separation agents, etc.) should be made unnecessary wherever possible and, innocuous when used. Dr. Concepcíon (Conchita) Jiménez-González, Director, Operational Sustainability, GlaxoSmithKline It was a green chemistry conference and the very famous synthetic chemist had just received a question about why he had chosen a solvent that was without question a very poor choice. You have to be realistic, chemists know intuitively what's best, and solvents don't matter. It's the chemistry that counts. I've heard this kind of remark repeatedly over many years, despite the fact that it goes against the spirit and letter of Principle 5. Solvents and mass separation agents of all kinds matter a lot to the chemistry not to mention the chemical process and the overall "greenness" of the reaction. In many cases, reactions wouldn't proceed without solvents and/or mass separation agents. To say that they don't matter, or that it's only the chemistry that counts is not just a logical fallacy, it's chemically incorrect. Solvents and separation agents provide for mass and energy transfer and without this, many reactions will not proceed. It has also been shown that solvents account for 50 – 80 percent of the mass in a standard batch chemical operation, depending on whether you include water or you don't. Moreover, solvents account for about 75% of the cumulative life cycle environmental impacts of a standard batch chemical operation. Solvents and mass separation agents also drive most of the energy consumption in a process. Think about it for a moment. Solvents are alternately heated, distilled, cooled, pumped, mixed, distilled under vacuum, filtered, etc. And that's before they may or may not be recycled. If they're not recycled, they are often incinerated. Solvents are also the major contributors to the overall toxicity profile and because of that, compose the majority of the materials of concern associated with a process. On average, they contribute the greatest concern for process safety issues because they are flammable and volatile, or under the right conditions, explosive. They also generally drive workers to don personal protective equipment of one kind or another. We will always need solvents, and with many things in chemical processes, it's a matter of impact trading. Optimize a solvent according to one green metric and many times, there are three others that don't look so good. The object is to choose solvents that make sense chemically, reduce the energy requirements, have the least toxicity, have the fewest life cycle environmental impacts and don't have major safety impacts. Solvents and separation agents do matter and despite one or more famous synthetic organic chemists may think. It is possible to make better choices, and that is what application of this principle should promote. 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. By Dr. David Constable, Director, ACS Green Chemistry Institute® In recent years I've begun to talk about the green chemistry and engineering's "forgotten principles," and Design for Energy Efficiency is one of them. Amongst synthetic organic chemists, no consideration is given to temperature or pressure. The chemist just follows a protocol to get a reaction to go to completion and to separate the desired product at as high a yield as possible. Energy, from the chemist's perspective, is irrelevant and for all intents and purposes, free. Just put the plug in the wall or the heating coil around the flask, or get the liquid nitrogen out of the dewar. For those that do think about energy, most if not all the attention that energy gets from chemists is devoted to heating, cooling, separations, electrochemistry, pumping and reluctantly, to calculations related to thermodynamics (e.g., Gibbs Free Energy). The attention is not in minimizing or considering where energy comes from or if it matters what form is used, it's just a given that we need to heat or cool or shove electrons into the reaction to make or break bonds. In reflecting on my own training as a chemist, I never was asked to convert any heating, cooling, pumping or electrochemical requirements to a cost for electricity, steam or some other utility. That may be done in chemical engineering, but not in chemistry. Energy is a key issue for the 21st century. A majority of the energy that is produced is based, and will continue to be based on fossil fuels. And most of the energy that is delivered to the point of use is lost in conversion and transmission. What this means is that if you look at the life cycle of energy production, and you look at how much energy is actually available for useful work at the point of need, it is less than 1 or 2 percent of the energy that was originally available in the fossil fuel. It is also true that most fossil fuel energy is used for transportation services of one kind or another and the second biggest use is in space heating and cooling. There are a tremendous number of opportunities for chemists to change this energy use profile, but it is my experience that very few chemists see themselves as being a part of either transportation or the built environment. If you think about where most chemists are trained around energy, and certainly chemical engineers are, it's around ΔH in the Gibbs Free Energy equation. Heats of formation, heats of vaporization, enthalpy, exothermic reactions, etc; these are what we think about. The interesting thing is that nature largely works with ΔS and weak forces of interaction. You don't see a tree doing photosynthesis at reflux using a solvent, or a cell membrane is not extruded at the melt temperature of something like polystyrene. There is so much more to energy and engaging chemists in thinking about energy than asking them to run reactions at ambient temperature and pressure. Reactions themselves are rarely where a majority of energy is used; most is used in solvent removal to set up for the next reaction, or to remove one solvent and replace it with another, or to isolate the desired product, or to remove impurities. Apart from hydrogenations or reactions that are oxygen or moisture sensitive, most reactions are done at atmospheric pressure. This doesn't mean that energy isn't important, it is just important in areas where most chemists are not focused. Once again, thinking about more than one part of the reaction or the process during the design of a new molecule is critical not only from the standpoint of energy, but also from many different angles. Energy—like thinking about how to arrange a synthesis to have the fewest number of steps, or use the lowest cost starting materials or any other aspect of interest to the synthetic or process chemist—is just another design parameter. Historically it has not been seen as that, but we can no longer afford to design new molecules in the absence of a detailed and extended consideration of how energy will be used. A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable. By Dr. Richard Wool, Professor of Chemical and Biomolecular Engineering and Director of the Affordable Composites from Renewable Materials program, University of Delaware. The concept of making all our future fuels, chemicals and materials from feedstocks that never deplete is an interesting concept which at first glance seems impracticable. Mankind currently removes fossil fuels, coal, oil and natural gas from the ground and extracts minerals for profit until they are exhausted. In particular, our fossil fuels for carbon-based chemicals and materials are being rapidly depleted in a predictable manner with the expected rise of global populations and expanding energy intensive economies on several continents. The impacts on human health and the environment are significant and present major challenges for our scientists and leaders in the next 50 years. Can we address these global problems by using Green Chemistry Principal #7? Yes, we will get our feedstock, as if by magic, from "thin air" and it will be renewable. The carbon in the air is in the form of carbon dioxide CO_2 and methane CH_4 and is removed by photosynthetic processes powered by the sun to form plants, trees, crops, algae, etc., which collectively we call "biomass". Nature produces about 170 billion tons of plant biomass annually, of which we currently use about 3.5 percent for human needs. It is estimated that about 40 billion tons of biomass, or about 25 percent of the annual production, would be required to completely generate a bio-based economy. The technical challenge in the use of such renewable feedstocks is to develop low energy, non-toxic pathways to convert the biomass to useful chemicals in a manner that does not generate more carbon than is being removed from "thin air"; the difference between C(in) from the air, and C(out) from the energy used, is the carbon footprint ΔC. Ideally, when using Principal #7, all carbon footprints by design should be positive such that C(in) >> C(out). This leads in a natural way to the reduction of global warming gasses impacting our current climate change. We should also insure that the new chemicals and materials derived from renewable resources are non-toxic or injurious to human health and the biosphere. In 2002, the U.S. Department of Energy in their Vision for Bioenergy and Bio-based Products in the United States stated: "By 2030, a well-established, economically viable, bioenergy, and bio-based products industry is expected to create new economic opportunities for rural America [globalization through localization], protect and enhance the environment, strengthen the U.S. energy independence, provide economic security, and deliver improved products to consumers." In the past 10 years, significant advances have been made in the development of fuels, chemicals and materials from renewable feedstocks. These for example, have included biodiesel from plant oils and algae, bioethanol and butanol from sugars and lignocellulose, plastics, foams and thermosets from lignin and plant oils, and even electronic materials from chicken feathers. In terms of Green Chemistry Principal #7, our future is bright and laced with optimism due to the ongoing fruitful collaborations between several disciplines involving biotechnology, agronomy, toxicology, physics, engineering and others, where new fuels, chemicals and materials are being derived from renewable feedstock from "thin air" with minimal impact on human health and the environment. Additional Resource Unnecessary derivatization (use of blocking groups, protection/deprotection, temporary modification of physical/chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste. By Peter J. Dunn, Green Chemistry Lead, Pfizer One of the key principles of green chemistry is to reduce the use of derivatives and protecting groups in the synthesis of target molecules. One of the best ways of doing this is the use of enzymes. Enzymes are so specific that they can often react with one site of the molecule and leave the rest of the molecule alone and hence protecting groups are often not required. A great example of the use of enzymes to avoid protecting groups and clean up processes is the industrial synthesis of semi-synthetic antibiotics such as ampicillin and amoxicillin. In the first industrial synthesis Penicillin G (R=H) is first protected as its silyl ester [R = $Si(Me)_3$] then reacted with phosphorus pentachloride at -40oC to form the chlorimidate 1 subsequent hydrolysis gives the desired 6-APA from which semi-synthetic penicillins are manufactured. (i) TMSCl then PCl_5, $PhNMe_2$, CH_2Cl_2, -40oC (ii) n-BuOH, -40oC, then H_2O, 0oC (iii) Pen-acylase, water This synthesis has been largely replaced by a newer enzymatic process using pen-acylase. This synthesis occurs in water at just above room temperature. The new synthesis has many advantages from a green perspective one of which is that the silyl protecting group is not required. More than 10,000 metric tons of 6-APA is made every year and much of it by the greener enzymatic process so this is a fantastic example of Green Chemistry making a real difference. Additional Resource The Importance of Green Chemistry in Process Research and Development Catalytic reagents (as selective as possible) are superior to stoichiometric reagents. Contributed by Roger A. Sheldon, Ph.D., Emeritus Professor of Biocatalysis and Organic Chemistry, Delft University of Technology and CEO of CLEA Technologies B.V. A primary goal of green chemistry is the minimization or preferably the elimination of waste in the manufacture of chemicals and allied products: "prevention is better than cure". This necessitates a paradigm shift in the concept of efficiency in organic synthesis, from one that is focused on chemical yield to one that assigns value to minimization of waste. What is the cause of waste? The key lies in the concept of atom economy: "synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product". In the reaction scheme we compare, for example, the reduction of a ketone to the corresponding secondary alcohol using sodium borohydride or molecular hydrogen as the reductant. Reduction with the former has an atom economy of 81% while reduction with the latter is 100% atom economic, that is everything ends up in the product and, in principle, there is no waste. Unfortunately, hydrogen does not react with ketones to any extent under normal conditions. For this, we need a catalyst such as palladium-on-charcoal. A catalyst is defined as "a substance that changes the velocity of a reaction without itself being changed in the process". It lowers the activation energy of the reaction but in so doing it is not consumed. This means that in principle at least, it can be used in small amounts and be recycled indefinitely, that is it doesn't generate any waste. Moreover, molecular hydrogen is also the least expensive reductant and, for this reason, catalytic hydrogenations are widely applied in the petrochemical industry, where the use of other reductants is generally not economically viable. It is only in the last two decades, however, following the emergence of green chemistry, that catalysis has been widely applied in the pharmaceutical and fine chemical industries, with the goal of minimizing the enormous amounts of waste generated by the use of stoichiometric inorganic reagents. This involves the use of the full breadth of catalysis: heterogeneous, homogeneous, organocatalysts and, more recently, Nature's own exquisite catalysts: enzymes. The latter are particularly effective at catalyzing highly selective processes with complex substrates under mild conditions and, hence, are finding broad applications in the pharmaceutical and allied industries. Moreover, they are expected to play an important role in the transition from a chemical industry based on non-renewable fossil resources to a more sustainable bio-based economy utilizing renewable biomass as the raw material, yet another noble goal of green chemistry. More Resources and Examples Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment. Contributed by Rich Williams, Founder and President at Environmental Science & Green Chemistry Consulting, LLC Green chemistry practitioners aspire to optimize the commercial function of a chemical while minimizing its hazard and risk. Hazard, the capability to cause harm, is an inherent characteristic arising, like function, from a chemical's stereochemistry (the content and arrangement of atoms). Green chemistry principles 3, 4, 5, and 12 guide designers to reduce the hazards of chemicals. Principle 10, however, guides the design of products that degrade after their commercial function in order to reduce risk or the probability of harm occurring. Risk is a function of both a molecule's inherent hazard AND exposure – contact between a chemical and a species. Degradation can eliminate significant exposure, thereby minimizing risk regardless of the hazard of the chemical involved. Exposure to persistent chemicals can be significant as a result of global dispersion enabled by properties such as volatility or sorption to particles and partitioning into organisms based on properties such as fat solubility. Regulators have established criteria (half-lives in water, soil, air) that define persistence within frameworks used to identify chemicals as PBT (Persistent, Bioaccumulative, Toxic). A green chemistry objective is to design out molecular features responsible for hazardous characteristics and risk. Trade-offs, or alternative approaches, must be evaluated when the molecular features to be designed in for commercial function overlap with those to be designed out to reduce hazard and risk. Biodegradation, hydrolysis, and photolysis can be designed into chemical products. In the same way that mechanistic toxicology knowledge is essential to identify and design out molecular features that are the basis for hazards, an understanding of the mechanisms of degradation and persistence are required to design in chemical features that promote degradation and eliminate features that promote persistence. Many persistent compounds are extensively chlorinated. Halogens such as chlorine are electron withdrawing, thereby inhibiting the enzyme systems of microbes because aerobic microbial degradation favors electron rich structures. Prediction methods that can guide the design of molecular architecture expected to degrade include rules of thumb linking structural features to degradability or persistence, databases of existing knowledge, models that evaluate biodegradability or PBT attributes, and experimental testing. All of these tools can be adapted to individual chemical sectors and specific objectives. Understanding the anticipated release and transport pathways for a chemical informs the selection of an effective design strategy. Degradation must occur within the relevant environmental compartment(s) and at a meaningful rate. Domestic wastewater typically passes through a vigorous bioreactor within wastewater treatment plants (WWTP). The consumer product industry has designed molecules for removal within these bioreactors. In the early 1960's, industry transitioned from non-biodegradable branched surfactants, which caused extensive foaming and other health problems in surface waters receiving WWTP effluent, to biodegradable linear alkyl benzene sulfonate based detergents – an approach to innovative design that continues today. Tools currently exist to enable the implementation of principle 10, but advances in mechanistic understandings linking molecular features to hazards and degradability will enable more comprehensive application of green chemistry to control hazard and risk. Effective communication across disciplines is also essential to provide designers with knowledge they can factor into the complexities of product design. Because of regulatory and business constraints, many product design decisions must be made relatively early. Predictive decision-making tools must provide confidence about hazard and risk in a way that is aligned with the timing and magnitude of development decisions, and most importantly, while there is still flexibility to alter a molecular design or product formulation. Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances. Contributed by Douglas Raynie, Assistant Professor, Chemistry & Biochemistry, South Dakota State University Imagine driving down a busy highway in a car with all of the windows painted an opaque black!!! While that scenario many not seem realistic (or safe), what if you had a 360° camera and the sensors and technology being developed for self-driving cars? Now, the safety of your commute is more ensured. This description, while applied to automobiles, is illustrative of the 11th principle of green chemistry. Just as we need real-time feedback for driving safety, real-time feedback is essential in proper functioning chemical processes. Most chemists are familiar with laboratory analysis from their undergraduate training. But analysis can also be performed in-line, on-line, or at-line in a chemical plant, a subdiscipline known as process analytical chemistry. Such analysis can detect changes in process temperature or pH prior to a reaction going out of control, poisoning of catalysts can be determined, and other deleterious events can be detected before a major incident occurs. Process analysis is of such importance that the US Food and Drug Administration encourages such an approach for the manufacture, design, and control of pharmaceutical manufacturing. Since 1984, an industry-academic partnership, the Center for Process Analytical Chemistry, has promoted research into emerging techniques for process analytical chemistry. While the traditional roles of analytical chemistry also advance green chemistry goals, the effective application of process analytical chemistry directly contributes to the safe and efficient operation of chemical plants worldwide. Additional Resource Center for Process Analysis & Control 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. Contributed by Shelly Bradley, Campus Chemical Compliance Director, Hendrix College; Dr. David C. Finster, Professor of Chemistry, Wittenberg University; and Dr. Tom Goodwin, Elbert L. Fausett Professor of Chemistry, Hendrix College Safety can be defined as the control of recognized hazards to achieve an acceptable level of risk. Green Chemistry Principle # 12 is known as the "Safety Principle". It may be the most overlooked of the twelve principles, yet it is the logical outcome of many of the other principles. In fact, it is practically impossible to achieve the goals of Principle 12 without the implementation of at least one of the others. Since the very essence of green chemistry is to "... reduce or eliminate the use or generation of hazardous substances" there is an intrinsic connection to laboratory safety. While there are a few exceptions, the majority of the Green Chemistry Principles will result in a scenario that is also safer. Under the umbrella of the Environmental Protection Agency (EPA), Green Chemistry's primary focus is clearly to make the environment safer. Materials and processes that are safer for the environment also are likely to be safer for the general public. However, another population that benefits from green chemistry and is not often mentioned is workers. The manufacturing or laboratory worker is often the first in-line person to benefit from hazard reductions. The health and safety of workers are under the purview of the Occupational Safety and Health Administration (OSHA). In a recent news release, OSHA unveiled a chemical management system designed to increase worker safety. The Hierarchy of Safety Controls as highlighted in OSHA's new Transitioning to Safer Chemicals Toolkit illustrates the difference between focusing on the control or hazard part of the safety definition. Traditional chemical safety models focus primarily on the control component of that definition. The graphic (adapted from OSHA) shows that the most effective means of increasing safety is eliminating the hazard component. Since the elimination of hazards is the basic tenet of Green Chemistry, this marriage of the ideas of Green Chemistry from both OSHA and EPA should have a synergistic impact on hazard reduction. Combining the forces of these two agencies toward a common goal may lead to conversations and changes that result in safer conditions for workers, a safer environment for the general public, and a safer planet for us all. References Cited: Manuele, F. A. Acceptable Risk, Professional Safety, 2010, 30-38 (accessed 11/22/2013)Anastas, P. T.; Warner, J. C. Green Chemistry: Theory and Practice; Oxford University Press; New York, 1998.US OSHA, OSHA releases new resources to better protect workers from hazardous chemicals, (accessed 11/22/2013)US OSHA, Transitioning to Safer Chemicals: A Toolkit for Employers and Workers, (accessed 11/22/2013)US OSHA, Why Transition to Safer Alternatives?, (accessed 11/22/2013) Research field in chemistry and chemical engineering This article is about the concept of the environmentally friendly design of chemical products and processes. For the journal, see Green Chemistry (journal). Green chemistry, similar to sustainable chemistry or circular chemistry,[1] is an area of chemistry and chemical engineering focused on the design of products and processes that minimize or eliminate the use and generation of hazardous substances.[2] While environmental chemistry focuses on the effects of polluting chemicals on nature, green chemistry focuses on the environmental impact of chemistry, including lowering consumption of nonrenewable resources and technological approaches for preventing pollution.[3][4][5][6][7][8] The overarching goals of green chemistry—namely, more resource-efficient and inherently safer design of molecules, materials, products, and processes—can be pursued in a wide range of contexts.[9] Definition Green chemistry (sustainable chemistry): Design of chemical products and processes that minimize or eliminate the use or generation of substances hazardous to humans, animals, plants, and the environment. Note 1: Modified from ref.[10] to be more general. Note 2: Green chemistry discusses the engineering concept of pollution prevention and zero waste both at laboratory and industrial scales. It encourages the use of economical and ecocompatible techniques that not only improve the yield but also bring down the cost of disposal of wastes at the end of a chemical process.[11] Green chemistry emerged from a variety of existing ideas and research efforts (such as atom economy and catalysis) in the period leading up to the 1990s, in the context of increasing attention to problems of chemical pollution and resource depletion. The development of green chemistry in Europe and the United States was linked to a shift in environmental problem-solving strategies: a movement from command and control regulation and mandated lowering of industrial emissions at the "end of the pipe," toward the active prevention of pollution through the innovative design of production technologies themselves. The set of concepts now recognized as green chemistry coalesced in the mid- to late-1990s, along with broader adoption of the term (which prevailed over competing terms such as "clean" and "sustainable" chemistry).[12][13] In the United States, the Environmental Protection Agency played a significant early role in fostering green chemistry through its pollution prevention programs, funding, and professional coordination. At the same time in the United Kingdom, researchers at the University of York, who used the term "clean technology" in the early 1990s, contributed to the establishment of the Green Chemistry Network within the Royal Society of Chemistry, and the launch of the journal Green Chemistry.[13] In 1991, in the Netherlands, a special issue called 'green chemistry' [groene chemie] was published in Chemisch Magazine. In the Dutch context, the umbrella term green chemistry was associated with the exploitation of biomass as a renewable feedstock.[14] In 1998, Paul Anastas (who then directed the Green Chemistry Program at the US EPA) and John C. Warner (then of Polaroid Corporation) published a set of principles to guide the practice of green chemistry.[15] The twelve principles address a range of ways to lower the environmental and health impacts of chemical production, and also indicate research priorities for the development of green chemistry technologies.[16] The principles cover such concepts as: the design of processes to maximize the amount of raw material that ends up in the product; the use of renewable material feedstocks and energy sources; the use of safe, environmentally benign substances, including solvents, whenever possible; the design of energy efficient processes; avoiding the production of waste, which is viewed as the ideal form of waste management. The twelve principles of green chemistry are:[17] Prevention: Preventing waste is better than treating or cleaning up waste after it is created. Atom economy: Synthetic methods should try to maximize the incorporation of all materials used in the process into the final product. This means that less waste will be generated as a result. Less hazardous chemical syntheses: Synthetic methods should avoid using or generating substances toxic to humans and/or the environment. Designing safer chemicals: Chemical products should be designed to achieve their desired function while being as non-toxic as possible. Safer solvents and auxiliaries: Auxiliary substances should be avoided wherever possible, and as non-hazardous as possible when they must be used. Design for energy efficiency: Energy requirements should be minimized, and processes should be conducted at ambient temperature and pressure whenever possible. Use of renewable feedstocks: Whenever it is practical to do so, renewable feedstocks or raw materials are preferable to non-renewable ones. Reduce derivatives: Unnecessary generation of derivatives—such as the use of protecting groups—should be minimized or avoided if possible; such steps require additional reagents and may generate additional waste. Catalysis: Catalytic reagents that can be used in small quantities to repeat a reaction are superior to stoichiometric reagents (ones that are consumed in a reaction). Design for degradation: Chemical products should be designed so that they do not pollute the environment; when their function is complete, they should break down into non-harmful products. Real-time analysis for pollution prevention: Analytical methodologies need to be further developed to permit real-time, in-process monitoring and control before hazardous substances form. Inherently safer chemistry for accident prevention: Whenever possible, the substances in a process, and the forms of those substances, should be chosen to minimize risks such as explosions, fires, and accidental releases. Attempts are being made not only to quantify the greenness of a chemical process but also to factor in other variables such as chemical yield, the price of reaction components, safety in handling chemicals, hardware demands, energy profile and ease of product workup and purification. In one quantitative study,[18] the reduction of nitrobenzene to aniline receives 64 points out of 100 marking it as an acceptable synthesis overall whereas a synthesis of an amide using HMDS is only described as adequate with a combined 32 points. Green chemistry is increasingly seen as a powerful tool that researchers must use to evaluate the environmental impact of nanotechnology.[19] As nano materials are developed, the environmental and human health impacts of both the products themselves and the processes to make them must be considered to ensure their long-term economic viability. There is a trend of nano material technology in the practice, however, people ignored the potential nanotoxicity. Therefore, people need to address further consideration on legal, ethical, safety, and regulatory issues associated with nanomaterials, [20] Main article: Green solvent The major application of solvents in human activities is in paints and coatings (46% of usage). Smaller volume applications include cleaning, de-greasing, adhesives, and in chemical synthesis.[21] Traditional solvents are often toxic or are chlorinated. Green solvents, on the other hand, are generally less harmful to health and the environment and preferably more sustainable. Ideally, solvents would be derived from renewable resources and biodegrade to innocuous, often a naturally occurring product.[22][23] However, the manufacture of solvents from biomass can be more harmful to the environment than making the same solvents from fossil fuels.[24] Thus the environmental impact of solvent manufacture must be considered when a solvent is being selected for a product or process.[25] Another factor to consider is the fate of the solvent after use. If the solvent is being used in an enclosed situation where solvent collection and recycling is feasible, then the energy cost and environmental harm associated with recycling should be considered; in such a situation water, which is energy-intensive to purify, may not be the greenest choice. On the other hand, a solvent contained in a consumer product is likely to be released into the environment upon use, and therefore the environmental impact of the solvent itself is more important than the energy cost and impact of solvent recycling; in such a case water is very likely to be a green choice. In short, the impact of the entire lifetime of the solvent, from cradle to grave (or cradle to cradle if recycled) must be considered. Thus the most comprehensive definition of a green solvent is the following: "a green solvent is the solvent that makes a product or process have the least environmental impact over its entire life cycle."[26] By definition, then, a solvent might be green for one application (because it results in less environmental harm than any other solvent that could be used for that application) and yet not be a green solvent for a different application. A classic example is water, which is a very green solvent for consumer products such as toilet bowl cleaner but is not a green solvent for the manufacture of polytetrafluoroethylene. For the production of that polymer, the use of water as solvent requires the addition of perfluorinated surfactants which are highly persistent. Instead, supercritical carbon dioxide seems to be the greenest solvent for that application because it performs well without any surfactant.[26] In summary, no solvent can be declared to be a "green solvent" unless the declaration is limited to a specific application. Novel or enhanced synthetic techniques can often provide improved environmental performance or enable better adherence to the principles of green chemistry. For example, the 2005 Nobel Prize for Chemistry was awarded to Yves Chauvin, Robert H. Grubbs and Richard R. Schrock, for the development of the metathesis method in organic synthesis, with explicit reference to its contribution to green chemistry and "smarter production."[27] A 2005 review identified three key developments in green chemistry in the field of organic synthesis: use of supercritical carbon dioxide as green solvent, aqueous hydrogen peroxide for clean oxidations and the use of hydrogen in asymmetric synthesis.[28] Some further examples of applied green chemistry are supercritical water oxidation, on water reactions, and dry media reactions.[citation needed] Bioengineering is also seen as a promising technique for achieving green chemistry goals. A number of important process chemicals can be synthesized in engineered organisms, such as shikimate, a Tamiflu precursor which is fermented by Roche in bacteria. Click chemistry is often cited[citation needed] as a style of chemical synthesis that is consistent with the goals of green chemistry. The concept of 'green pharmacy' has recently been articulated based on similar principles.[29] In 1996, Dow Chemical won the 1996 Greener Reaction Conditions award for their 100% carbon dioxide blowing agent for polystyrene foam production. Polystyrene foam is a common material used in packing and food transportation. Seven hundred million pounds are produced each year in the United States alone. Traditionally, CFC and other ozone-depleting chemicals were used in the production process of the foam sheets, presenting a serious environmental hazard. Flammable, explosive, and, in some cases toxic hydrocarbons have also been used as CFC replacements, but they present their own problems. Dow Chemical discovered that supercritical carbon dioxide works equally as well as a blowing agent, without the need for hazardous substances, allowing the polystyrene to be more easily recycled. The CO_2 used in the process is reused from other industries, so the net carbon released from the process is zero. Addressing principle #2 is the peroxide process for producing hydrazine without cogenerating salt. Hydrazine is traditionally produced by the Olin Raschig process from sodium hypochlorite (the active ingredient in many bleaches) and ammonia. The net reaction produces one equivalent of sodium chloride for every equivalent of the targeted product hydrazine:[30] $NaOCl + 2\ NH_3 \rightarrow H_2N\text{-}NH_2 + NaCl + H_2O$ In the greener peroxide process hydrogen peroxide is employed as the oxidant and the side product is water. The net conversion follows: $2\ NH_3 + H_2O_2 \rightarrow H_2N\text{-}NH_2 + 2\ H_2O$ Addressing principle #4, this process does not require auxiliary extracting solvents. Methyl ethyl ketone is used as a carrier for the hydrazine, the intermediate ketazine phase separates from the reaction mixture, facilitating workup without the need of an extracting solvent. Addressing principle #7 is a green route to 1,3-propanediol, which is traditionally generated from petrochemical precursors. It can be produced from renewable precursors via the bioseparation of 1,3-propanediol using a genetically modified strain of E. coli.[31] This diol is used to make new polyesters for the manufacture of carpets. Lactide In 2002, Cargill Dow (now NatureWorks) won the Greener Reaction Conditions Award for their improved method for polymerization of polylactic acid . Unfortunately, lactide-base polymers do not perform well and the project was discontinued by Dow soon after the award. Lactic acid is produced by fermenting corn and converted to lactide, the cyclic dimer ester of lactic acid using an efficient, tin-catalyzed cyclization. The L,L-lactide enantiomer is isolated by distillation and polymerized in the melt to make a crystallizable polymer, which has some applications including textiles and apparel, cutlery, and food packaging. Wal-Mart has announced that it is using/will use PLA for its produce packaging. The NatureWorks PLA process substitutes renewable materials for petroleum feedstocks, doesn't require the use of hazardous organic solvents typical in other PLA processes, and results in a high-quality polymer that is recyclable and compostable. In 2003 Shaw Industries selected a combination of polyolefin resins as the base polymer of choice for EcoWorx due to the low toxicity of its feedstocks, superior adhesion properties, dimensional stability, and its ability to be recycled. The EcoWorx compound also had to be designed to be compatible with nylon carpet fiber. Although EcoWorx may be recovered from any fiber type, nylon-6 provides a significant advantage. Polyolefins are compatible with known nylon-6 depolymerization methods. PVC interferes with those processes. Nylon-6 chemistry is well-known and not addressed in first-generation production. From its inception, EcoWorx met all of the design criteria necessary to satisfy the needs of the marketplace from a performance, health, and environmental standpoint. Research indicated that separation of the fiber and backing through elutriation, grinding, and air separation proved to be the best way to recover the face and backing components, but an infrastructure for returning postconsumer EcoWorx to the elutriation process was necessary. Research also indicated that the postconsumer carpet tile had a positive economic value at the end of its useful life. EcoWorx is recognized by MBDC as a certified cradle-to-cradle design. Trans and cis fatty acids In 2005, Archer Daniels Midland (ADM) and Novozymes won the Greener Synthetic Pathways Award for their enzyme interesterification process. In response to the U.S. Food and Drug Administration (FDA) mandated labeling of trans-fats on nutritional information by January 1, 2006, Novozymes and ADM worked together to develop a clean, enzymatic process for the interesterification of oils and fats by interchanging saturated and unsaturated fatty acids. The result is commercially viable products without trans-fats. In addition to the human health benefits of eliminating trans-fats, the process has reduced the use of toxic chemicals and water, prevents vast amounts of byproducts, and reduces the amount of fats and oils wasted. In 2011, the Outstanding Green Chemistry Accomplishments by a Small Business Award went to BioAmber Inc. for integrated production and downstream applications of bio-based succinic acid. Succinic acid is a platform chemical that is an important starting material in the formulations of everyday products. Traditionally, succinic acid is produced from petroleum-based feedstocks. BioAmber has developed process and technology that produces succinic acid from the fermentation of renewable feedstocks at a lower cost and lower energy expenditure than the petroleum equivalent while sequestering CO_2 rather than emitting it.[32] However, lower prices of oil precipitated the company into

bankruptcy [33] and bio-sourced succinic acid is now barely made.[34] Several laboratory chemicals are controversial from the perspective of Green chemistry. The Massachusetts Institute of Technology created a "Green" Alternatives Wizard [1] to help identify alternatives. Ethidium bromide, xylene, mercury, and formaldehyde have been identified as "worst offenders" which have alternatives.[35] Solvents in particular make a large contribution to the environmental impact of chemical manufacturing and there is a growing focus on introducing Greener solvents into the earliest stage of development of these processes: laboratory-scale reaction and purification methods.[36] In the Pharmaceutical Industry, both GSK[37] and Pfizer[38] have published Solvent Selection Guides for their Drug Discovery chemists. In 2007, The EU put into place the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) program, which requires companies to provide data showing that their products are safe. This regulation (1907/2006) ensures not only the assessment of the chemicals' hazards as well as risks during their uses but also includes measures for banning or restricting/authorising uses of specific substances. ECHA, the EU Chemicals Agency in Helsinki, is implementing the regulation whereas the enforcement lies with the EU member states. The United States formed the Environmental Protection Agency (EPA) in 1970 to protect human and environmental health by creating and enforcing environmental regulation. Green chemistry builds on the EPA's goals by encouraging chemists and engineers to design chemicals, processes, and products that avoid the creation of toxins and waste.[39] The U.S. law that governs the majority of industrial chemicals (excluding pesticides, foods, and pharmaceuticals) is the Toxic Substances Control Act (TSCA) of 1976. Examining the role of regulatory programs in shaping the development of green chemistry in the United States, analysts have revealed structural flaws and long-standing weaknesses in TSCA; for example, a 2006 report to the California Legislature concludes that TSCA has produced a domestic chemicals market that discounts the hazardous properties of chemicals relative to their function, price, and performance.[40] Scholars have argued that such market conditions represent a key barrier to the scientific, technical, and commercial success of green chemistry in the U.S., and fundamental policy changes are needed to correct these weaknesses.[41] Passed in 1990, the Pollution Prevention Act helped foster new approaches for dealing with pollution by preventing environmental problems before they happen. Green chemistry grew in popularity in the United States after the Pollution Prevention Act of 1990 was passed. This Act declared that pollution should be lowered by improving designs and products rather than treatment and disposal. These regulations encouraged chemists to reimagine pollution and research ways to limit the toxins in the atmosphere. In 1991, the EPA Office of Pollution Prevention and Toxics created a research grant program encouraging the research and recreation of chemical products and processes to limit the impact on the environment and human health.[42] The EPA hosts The Green Chemistry Challenge each year to incentivize the economic and environmental benefits of developing and utilizing green chemistry.[43] In 2008, the State of California approved two laws aiming to encourage green chemistry, launching the California Green Chemistry Initiative. One of these statutes required California's Department of Toxic Substances Control (DTSC) to develop new regulations to prioritize "chemicals of concern" and promote the substitution of hazardous chemicals with safer alternatives. The resulting regulations took effect in 2013, initiating DTSC's Safer Consumer Products Program.[44] Green Chemistry (RSC) Green Chemistry Letters and Reviews (Open Access) (Taylor & Francis) ChemSusChem (Wiley) ACS Sustainable Chemistry & Engineering (ACS) There are ambiguities in the definition of green chemistry and how it is understood among broader science, policy, and business communities. Even within chemistry, researchers have used the term "green chemistry" to describe a range of work independently of the framework put forward by Anastas and Warner (i.e., the 12 principles).[13] While not all uses of the term are legitimate (see greenwashing), many are, and the authoritative status of any single definition is uncertain. More broadly, the idea of green chemistry can easily be linked (or confused) with related concepts like green engineering, environmental design, or sustainability in general. Green chemistry's complexity and multifaceted nature makes it difficult to devise clear and simple metrics. As a result, "what is green" is often open to debate.[45] Several scientific societies have created awards to encourage research in green chemistry. Australia's Green Chemistry Challenge Awards overseen by The Royal Australian Chemical Institute (RACI). The Canadian Green Chemistry Medal.[46] In Italy, Green Chemistry activities center around an inter-university consortium known as INCA.[47] In Japan, The Green & Sustainable Chemistry Network oversees the GSC awards program.[48] In the United Kingdom, the Green Chemical Technology Awards are given by Crystal Faraday.[49] In the US, the Presidential Green Chemistry Challenge Awards recognize individuals and businesses.[50][51] Chemistry portal Bioremediation – a technique that generally falls outside the scope of green chemistry Environmental engineering science Green Chemistry (journal) – published by the Royal Society of Chemistry Green chemistry metrics Green computing – a similar initiative in the area of computing Green engineering Substitution of dangerous chemicals Sustainable engineering ^ Mutlu, Hatice; Barner, Leonie (2022-06-03). "Getting the Terms Right: Green, Sustainable, or Circular Chemistry?". 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Retrieved 2006-07-31. ^ "Information about the Presidential Green Chemistry Challenge". 2013-02-13. Archived from the original on 2015-03-17. Retrieved 2014-08-10. Retrieved from " Green chemistry is the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances. Green chemistry applies across the life cycle of a chemical product, including its design, manufacture, use, and ultimate disposal. Green chemistry: Prevents pollution at the molecular level Is a philosophy that applies to all areas of chemistry, not a single discipline of chemistry Applies innovative scientific solutions to real-world environmental problems Results in source reduction because it prevents the generation of pollution Reduces the negative impacts of chemical products and processes on human health and the environment Lessens and sometimes eliminates hazards from existing products and processes Designs chemical products and processes to reduce their intrinsic hazards How Green Chemistry Prevents Pollution Green chemistry reduces pollution at its source by minimizing or eliminating the hazards of chemical feedstocks, reagents, solvents, and products. This is not the same as cleaning up pollution (also called remediation), which involves treating waste streams (end-of-the-pipe treatment) or cleanup of environmental spills and other releases. Remediation may include separating hazardous chemicals from other materials, then treating them so they are no longer hazardous or concentrating them for safe disposal. Most remediation activities do not involve green chemistry. Remediation removes hazardous materials from the environment; on the other hand, green chemistry keeps the hazardous materials from being generated in the first place. If a technology reduces or eliminates the hazardous chemicals used to clean up environmental contaminants, this technology would also qualify as a green chemistry technology. One example is replacing a hazardous sorbent [chemical] used to capture mercury from the air for safe disposal with an effective, but nonhazardous sorbent. Using the nonhazardous sorbent means that the hazardous sorbent is never manufactured and so the remediation technology meets the definition of green chemistry. The 12 Principles of Green Chemistry 1. Prevent waste: Design chemical syntheses to prevent waste. Leave no waste to treat or clean up. 2. Maximize atom economy: Design syntheses so that the final product contains the maximum proportion of the starting materials. Waste few or no atoms. 3. Design less hazardous chemical syntheses: Design syntheses to use and generate substances with little or no toxicity to either humans or the environment. 4. Design safer chemicals and products: Design chemical products that are fully effective yet have little or no toxicity. 5. Use safer solvents and reaction conditions: Avoid using solvents, separation agents, or other auxiliary chemicals. If you must use these chemicals, use safer ones. 6. Increase energy efficiency: Run chemical reactions at room temperature and pressure whenever possible. 7. Use renewable feedstocks: Use starting materials (also known as feedstocks) that are renewable rather than depletable. The source of renewable feedstocks is often agricultural products or the wastes of other processes; depletable feedstocks are often fossil fuels (petroleum, natural gas, or coal) or mining operations. 8. Avoid chemical derivatives: Avoid using blocking or protecting groups or any temporary modifications if possible. Derivatives use additional reagents and generate waste. 9. Use catalysts, not stoichiometric reagents: Minimize waste by using catalytic reactions. Catalysts are effective in small amounts and can carry out a single reaction many times. They are preferable to stoichiometric reagents, which are used in excess and carry out a reaction only once. 10. Design chemicals and products to degrade after use: Design chemical products to break down to innocuous substances after use so that they do not accumulate in the environment. 11. Analyze in real time to prevent pollution: Include in-process, real-time monitoring and control during syntheses to minimize or eliminate the formation of byproducts. 12. Minimize the potential for accidents: Design chemicals and their physical forms (solid, liquid, or gas) to minimize the potential for chemical accidents including explosions, fires, and releases to the environment. 12 Principles of Green Chemistry Bookmark Download a bookmark showing the 12 principles of green chemistry. Green Chemistry and the Pollution Prevention Act of 1990 In the federal Pollution Prevention Act of 1990, Congress declared that it is "the national policy of the United States that pollution should be prevented or reduced at the source whenever feasible; pollution that cannot be prevented should be recycled in an environmentally safe manner, whenever feasible; pollution that cannot be prevented or recycled should be treated in an environmentally safe manner whenever feasible; and disposal or other release into the environment should be employed only as a last resort and should be conducted in an environmentally safe manner." The law defines source reduction as any practice which reduces the amount of any hazardous substance, pollutant, or contaminant entering any waste stream or otherwise released into the environment (including fugitive emissions) prior to recycling, treatment, or disposal; and, reduces the hazards to public health and the environment associated with the release of such substances, pollutants, or contaminants. The term includes equipment or technology. modifications, process or procedure modifications, reformulation or redesign of products, substitution of raw materials and improvements in housekeeping, maintenance, training, or inventory control."