BIOMIMICRY'S LIFE PRINCIPLES

LIFE CREATES CONDITIONS CONDUCIVE TO LIFE

Optimize rather than maximize

Leveraging interdependence

Benign manufacturing

LIFE ADAPTS AND EVOLVES

Locally attuned and responsive

Integrates cyclical processes

Resilient

Safer Chemistry Through Biomimicry

Reducing Potentially Harmful Impacts of TRI Chemicals

Introduction: Biomimicry is the conscious emulation of life's patterns to solve human problems. The core idea is that Nature, after 3.8 billion years of research and development, has already solved many of the problems we are grappling with and done it in a way that fits in with our natural world. Life must synthesize, use, and dispose of chemicals in the same environment in which it eats, sleeps, and rears its young. By necessity, life does this in a sustainable way. What better source for inspired solutions than Nature's time tested chemistry?

Challenge to Nature: The U.S. EPA Region 8 office partnered with the Biomimicry Guild to test biomimicry as a methodology to identify innovations for reducing the potentially harmful effects of Toxic Release Inventory (TRI) chemicals. Bisphenol-A (BPA) was selected as the target chemical for this analysis. BPA is found in many products and is most notably used in making plastic. BPA was selected based on environmental quantities reported to TRI for 2008 and its status as an EPA chemical of concern. TRI 2008 data indicates it as (1) the chemical with the highest disposal and release quantities, (2) the only chemical with increasing percent change in disposal and releases from 2007 levels, (3) the chemical with the highest waste management quantities, and (4) the chemical with second highest air emissions quantities.

At the heart of the biomimicry methodology is the function question: How does Nature do (anything)? Whatever the challenge, it has to be broken down to one or more function questions in order to find like functions in Nature. The research team looked at where and how BPA is used by conducting an analysis of industrial sectors reporting BPA. Ultimately, this analysis led to selecting controlled color change for thermal and carbonless paper as the target function.

Thermal and Carbonless Paper — What is the Problem?

Thermal and carbonless paper consists of a layer of color-development chemicals covering the whole surface on the side to be printed. The color-development chemicals include a leuco dye (crystal violet lactone) in its colorless form, a color developer (BPA), and a solvent. The leuco dye and BPA are each micro-encapsulated to prevent reaction until heat or pressure causes the capsules to rupture, allowing BPA to react with and darken the leuco dye. Thermal and carbonless printing papers are regularly used as cash register receipts, luggage tags, faxes, and labels. Experiments conducted with cash register receipts suggest that ten times more BPA can be transmitted to wet or greasy skin compared to dry skin; BPA may penetrate to depths where it can no longer be washed off. Even low doses of BPA are an issue because it has been shown to mimic natural estrogens that may impact the endocrine system even at very low does; the major concern is exposure of the developing fetus to low-does of BPA.

Challenge to Biology

Methodology: A search of both the primary and secondary literature resulted in a list of 21 ways that Nature changes color. For each strategy, the Biomimicry Guild provided the common and scientific name of the organism, a brief description of the strategy, the color changes that occur, whether or not the change is reversible, the color change trigger, colorant, and a citation where available. The strategies included, among others, crab spiders that change from white to yellow, tomato hornworms that change from black to green, sugar maple leaves that change from green to red, tropical flatfish that turn from beige to dark brown/black, and squids that can turn almost any combination of color, iridescence, and texture. This broad but "shallow dive" into Nature's color-changing strategies is an early step in the biomimicry process.

What is the Toxics Release Inventory Program?

In 1984, an industrial accident released a deadly cloud of methyl isocyanate and killed thousands of people in Bhopal, India. Shortly thereafter, a serious chemical release occurred at a sister plant in West Virginia. These incidents underscored demands by industrial workers and communities in several states for information on hazardous materials.

Public interest and environmental organizations around the country accelerated demands for information on toxic chemicals being released "beyond the fence line" -- outside of the facility. Against this background, the Emergency Planning and Community Right-to-Know Act (EPCRA) was enacted in 1986. EPCRA's primary purpose is to inform communities and citizens of chemical hazards in their areas. EPCRA Section 313 requires EPA and the States to collect data annually on releases and transfers of certain toxic chemicals from industrial facilities and make the data available to the public in the Toxics Release Inventory (TRI).

In 1990 Congress passed the Pollution Prevention Act which requires facilities to report additional data on waste management and source reduction activities to EPA under TRI. The goal of the Toxics Release Inventory Program is to provide communities with information about toxic chemical releases and waste management activities and to support informed decision making at all levels by industry, government, non-governmental organizations, and the public.

The TRI Program compiles the TRI data submitted by regulated facilities each year and makes the data available through the TRI Data and Tools web pages on the Toxic Release Inventory (http://www.epa.gov/tri) website. This website provide access to specific data and trend information on individual facilities, counties and states, or the nation as a whole. In addition you can analyze the data by industry, by specific media (e.g., air, land, water) and by chemical.

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Nature Strategies for Color Change — Three Examples

Fuligo septica
Acellular (true) slime moulds are capable of a transition to the stage of sclerotium – a dormant form of plasmodium produced under unfavourable environmental conditions. Darkening of the sclerotia (a vegetative, resting food-storage body composed of a compact mass of hardened mycelia) is most probably a pathological phenomenon connected with the impairment of water balance during sclerotization.

Reversible Change
No

Color Change Trigger

Colorant
Melanin

*Slime Mould
Photo by Flickr user “the photo workshop”

Pentapodus paradiseus
This fish has distinct reflective stripes on its head and body. The reflective stripes contain a dense layer of physiologically active iridophores, which act as multilayer reflectors. The wavelengths reflected by these stripes can change from blue to red in 0.25 seconds. Iridophore cells contain plates that are, on average, 51.4·nm thick. This thickness produces a stack, which acts as an ideal quarter-wavelength multilayer reflector (equal optical thickness of plates and spaces) in the blue, but not the red, region of the spectrum. Color change is associated with changes in the distance between adjoining reflecting plates. Reflective changes are controlled by the sympathetic nervous system; noradrenaline norepinephrine causes the reflected wavelengths to change to the longer end of the spectrum, adenosine causes the reverse effect.

Reversible Change
Yes

Color Change Trigger
Noradrenaline, adenosine

Colorant
Structural (no pigment)

*Paradise whiptail
Photo by Flickr user “Matt & Miche”

Anthocyanins, found in vegetables as well as flowers and fruits, can be red to purple depending on pH. The resonating flavylium structure accounts for anthocyanins’ depth and intensity of color. While there are six common anthocyanidins, more than 540 anthocyanin pigments have been identified in nature.

Reversible Change
Yes

Color Change Trigger
Sugar, pH

Colorant
Anthocyanins

*
Vegetables
Photo by Flickr user “docman”

Next Steps:

EPA Region 8 worked with the Biomimicry Guild to test biomimicry as a methodology to identify innovations for reducing the potentially harmful effects of TRI chemicals. Bisphenol-A (BPA) was selected as the target chemical based on environmental release quantities reported to TRI for 2008 and its status as an EPA chemical of concern. BPA's use as a color-developer in thermal and carbonless paper was chosen as the target chemical application. A comprehensive survey of the scientific literature revealed almost two dozen natural strategies for color change in organisms ranging from crab spiders that change from white to yellow, tomato hornworms that change from black to green, sugar maple leaves that change from green to red, tropical flatfish that turn from beige to dark brown/ black, and squids that can turn to almost any combination of color, iridescence, and texture. Color change strategies include oxidation to colored compounds, hormone control of the motion of pigment-containing organelles within individual color cells, and pigment-free layered structures that play with incoming light to produce color.

Three major types of color-changing strategies emerge from the shallow-dive research: (1) pigment-based color changes, (2) pigment-free, structural-based color changes, and (3) combination pigment-based and structural-based color changes. Chemical triggers are the most often cited initiators of color-change, including hormones, neurotransmitters, oxidizing agents, sugars, and acids/bases. Other color change triggers include light (UV, visible, and polarized) and temperature changes. Anthocyanins (flavonoids) and melanins are less mentioned colorants, followed by carotenes (terpenes).

Nature-inspired alternatives to BPA in thermal paper might take one of two routes. The first is to develop a non-toxic substitute for BPA while preserving the current two-chemical encapsutlation technology triggered by heat or pressure. The shallow dive done for this project suggest melanin or anthrocyanins might be promising candidates as colorants, so the next step would be to select several of the melanin and anthrocyanin strategies for more detailed studies of their chemical color change chemistry. The Biomimicry Guild refers to this step as a "deep dive" into the primary scientific literature.

The second route is to develop a completely new technology for use as cash register receipts, luggage tags, faxes, labels, etc. Imagine a technology that requires no pigment, no color developer, and no solvent, but instead relies on modification of the nano-structure of the substrate to create the desired pattern. In this case the next step would be to select one or more of the pigment-free, structure-based strategies for a deep dive research.

The result of the deep dives would be used to identify any common principles at work across strategies and taxa. Once identified, these common principles help formulate plans for biomimetic innovations to be shared with a collaborating laboratory that could develop a proof of concept prototype.

References:

Information for this report was provided to EPA Region 8 through a contract with the Biomimicry Guild.
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