GREEN, SAFE AND SUSTAINABLE CHEMISTRY :REPOSITIONING CHEMISTRY AS A CENTRAL SCIENCE

Industrial Green Chemistry World Convention 2015

Mumbai, 5 December 2015

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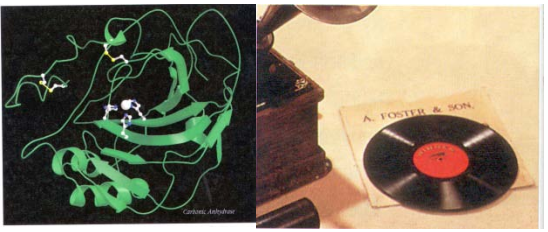
CHEMISTRY IS THE CENTRAL, USEFUL AND CREATIVE SCIENCE

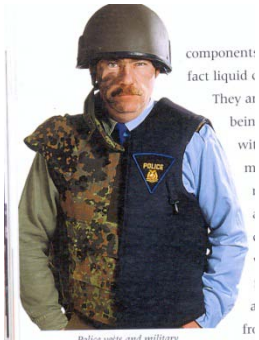
- R.Breslow

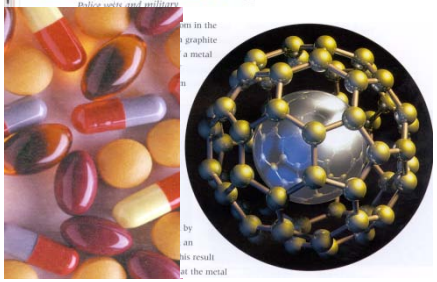
Central

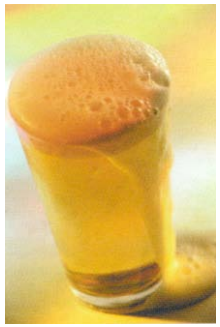
Underpins many other scientific disciplines

Biology, geology, material science







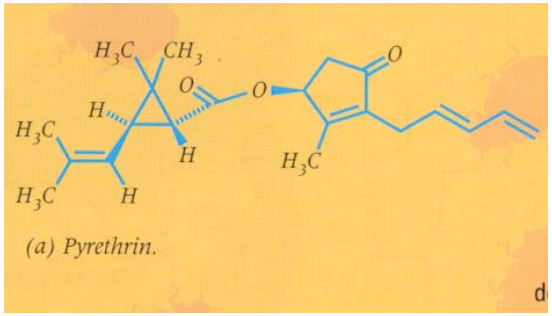


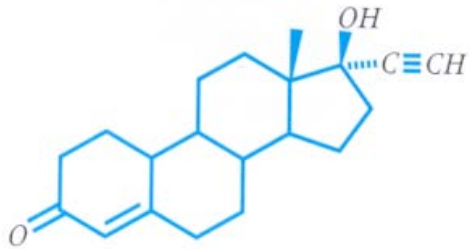
Useful

Provides many materials essential to everyday life, knowledge to better human, animal and plant care, better food, environment

Creative

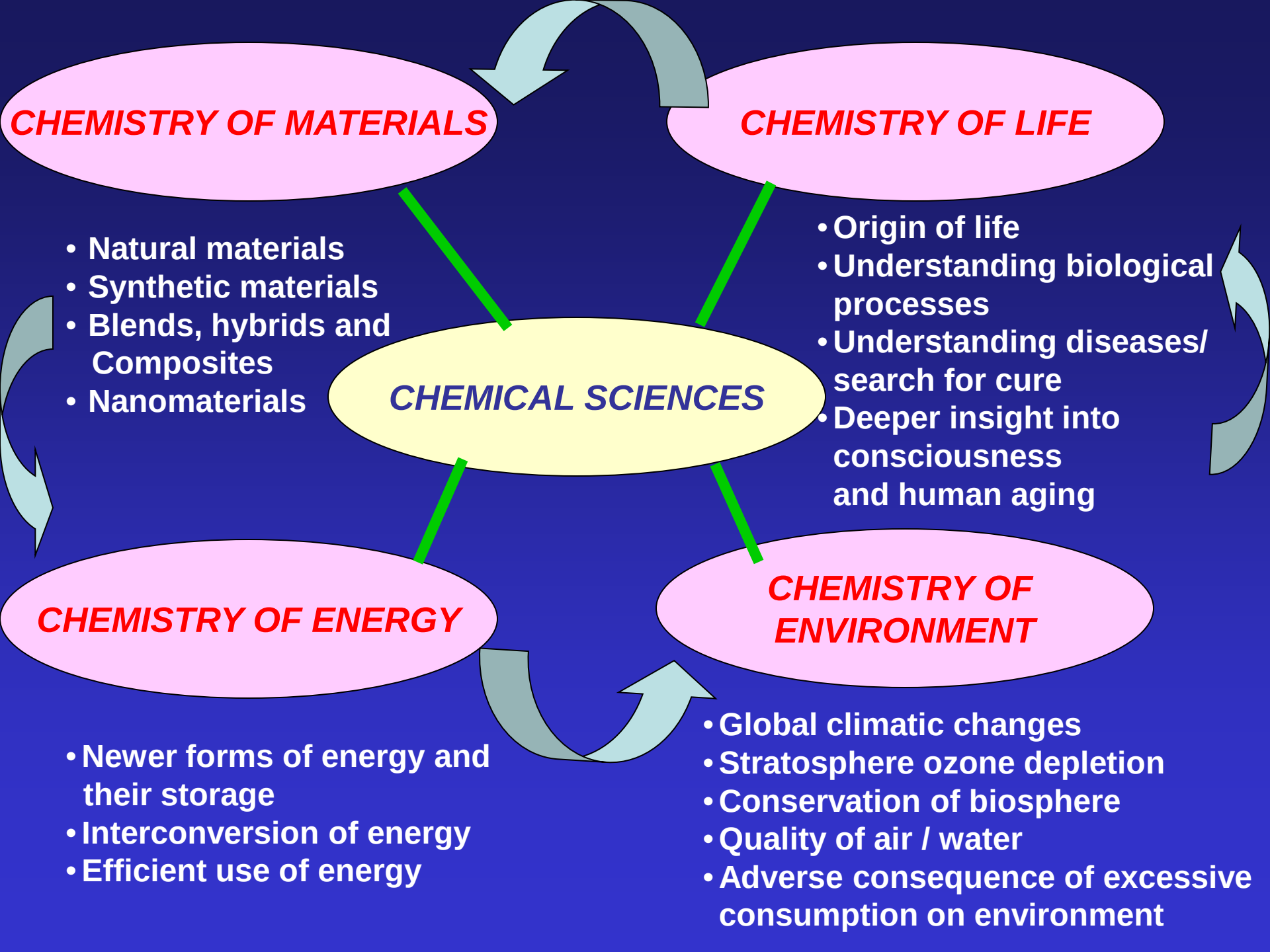
Designs structures with new and unique properties





Norethindrone (Norlutin)

Figure 14. Norlutin, the first contraceptive pil


CHEMISTRY OF MATERIALS
CHEMISTRY OF LIFE
• Natural materials
• Synthetic materials
• Blends, hybrids and Composites
• Nanomaterials
CHEMICAL SCIENCES
• Origin of life
• Understanding biological processes
• Understanding diseases/ search for cure
• Deeper insight into consciousness and human aging
CHEMISTRY OF ENERGY
CHEMISTRY OF ENVIRONMENT
• Newer forms of energy and their storage
• Interconversion of energy
• Efficient use of energy
• Global climatic changes
• Stratosphere ozone depletion
• Conservation of biosphere
• Quality of air / water
• Adverse consequence of excessive consumption on environment

CHEMISTRY'S HOARY PAST

- **Aspirin, Indigo, ammonia, Antibiotics, Lipitor, Nylon, Teflon, Polyethylene, Rayon, Synthetic Rubber, Fuels……**
- **Nylon stockings, Hula Hoop, Packaged Foods, Bullet Proof Vests……..**

IS THE FUTURE BRIGHT ?

Chemistry no longer captures the public imagination

Why is the public perception of Chemistry so low ?

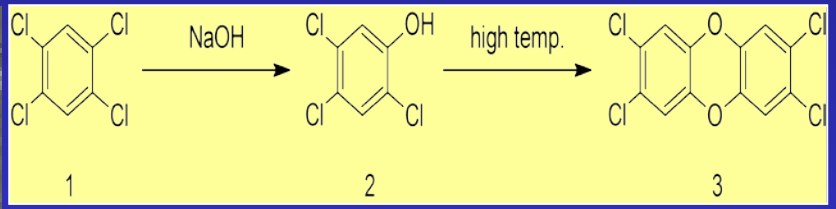
PUBLIC PERCEPTION OF CHEMISTRY : NOT VERY LAUDATORY

- Chemistry has become invisible to the public
- Chemistry is considered “mature” technologically
- Chemistry is associated with pollution/global warming
- “Good” and “Bad” are not balanced in perceptions of chemistry

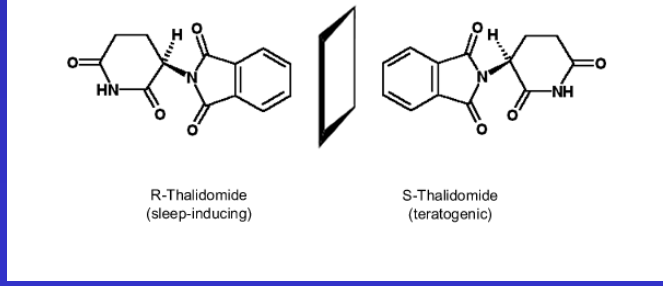
CHEMISTRY : A MALIGNED SCIENCE

A child victim of the Bhopal gas disaster.

- Minamata
- Love Canal
- Seveso
- Bhopal
- Thalidomide
- DDT

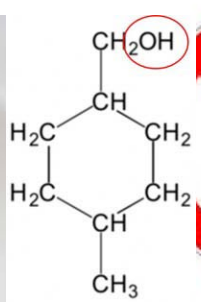


$$H_3C-Hg^{+}\ X^{-}$$



If these were mistakes of the past, are we wiser now ?

Everything is not in the past !



Freedom Industries, W. Virginia, January 2014

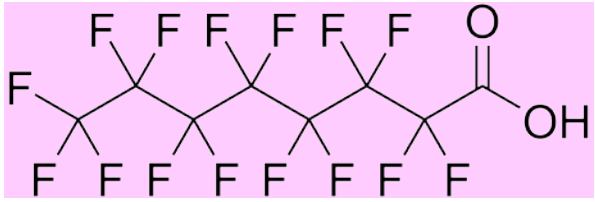
DuPont, Laporte, Texas November 2014

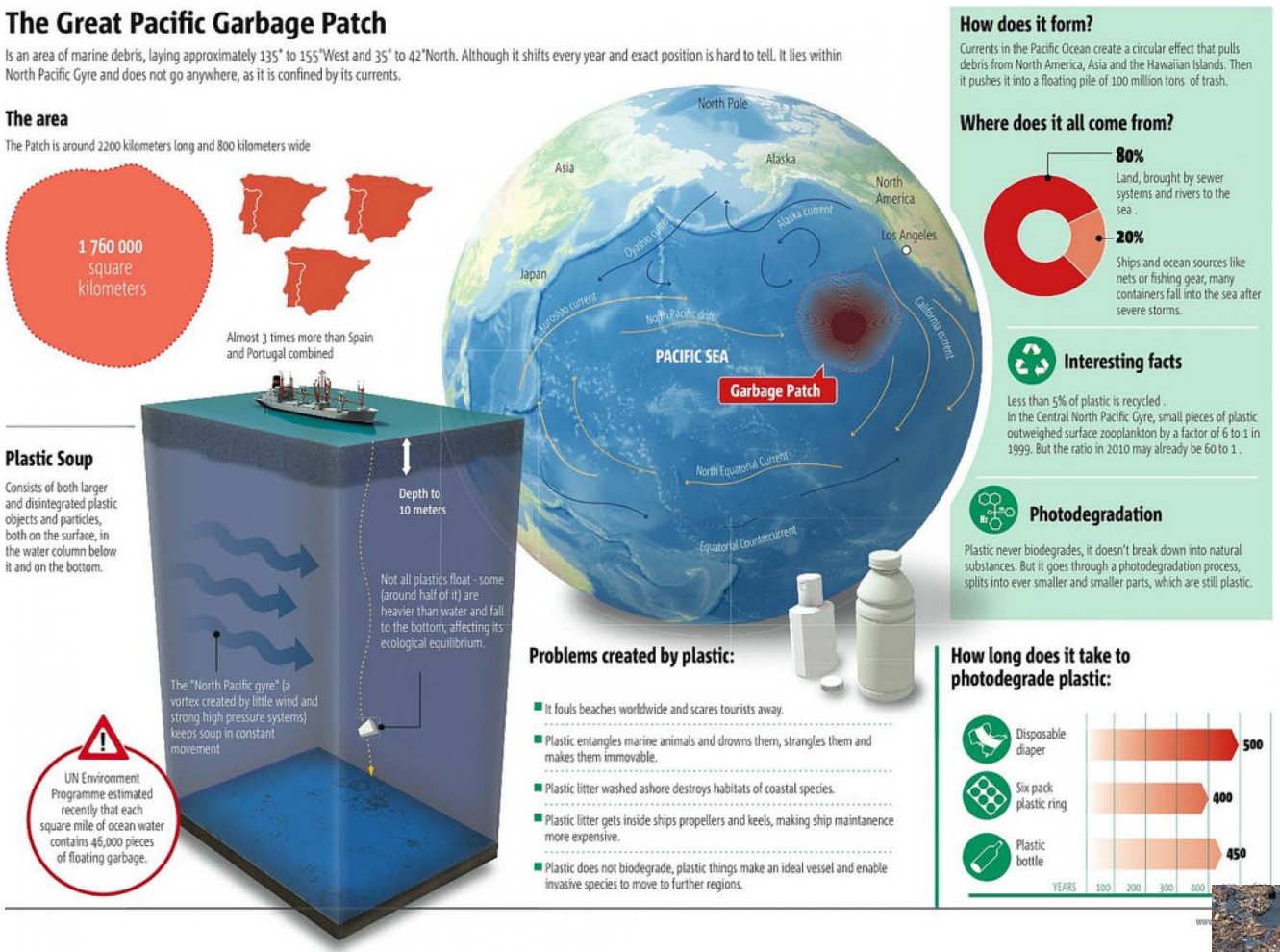
Keeping Tabs

How DuPont compares with other chemical companies in the number of accidents reported to the U.S. Environmental Protection Agency over a five-year span:

Company	Number of employees	Number of accidents	Accidents per employee
PPG Industries	1,380	6	0.0043
Air Products	1,435	6	0.0042
DuPont	**11,191**	**33**	**0.0029**
Mosaic	1,626	3	0.0018
Praxair	1,116	2	0.0018
LyondellBasell	4,878	8	0.0016
Dow	19,232	31	0.0016
BASF	5,767	6	0.0010
Bayer	5,155	4	0.0008
Chevron Phillips	2,669	2	0.0007

Source: Wall Street Journal analysis of EPA data collected by the Center for Effective Government in May 2013. The Wall Street Journal





The patch contains 270,000 tons of plastic waste
Microplastics upto <5 mm dia
Leachates detected : nonylphenol, Triclosan, PBDE 47 etc

http://visual.ly/great-pacific-garbage-patch

There is an estimated 200 million tons of plastics litter in our oceans
Our oceans can be devoid of life in the not too distant future if nothing is done to stem this

GREEN, SAFE AND SUSTAINABLE CHEMISTRY : IMPERATIVE FOR THE FUTURE OF CHEMISTRY

Safe chemistry and industry

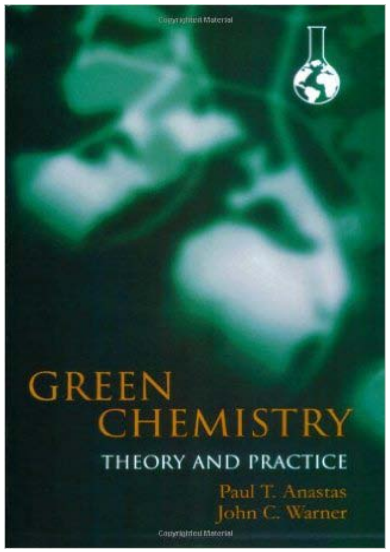
Green chemistry

Sustainability

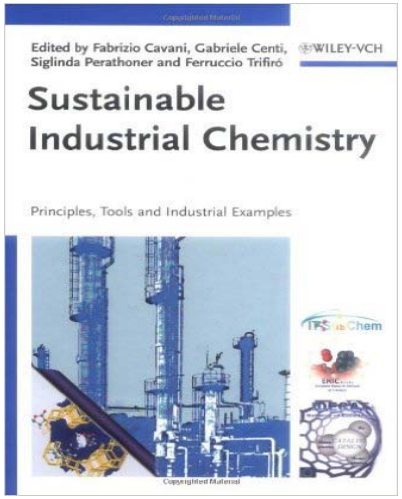
Sustainable chemistry

Economically viable and affordable chemistry

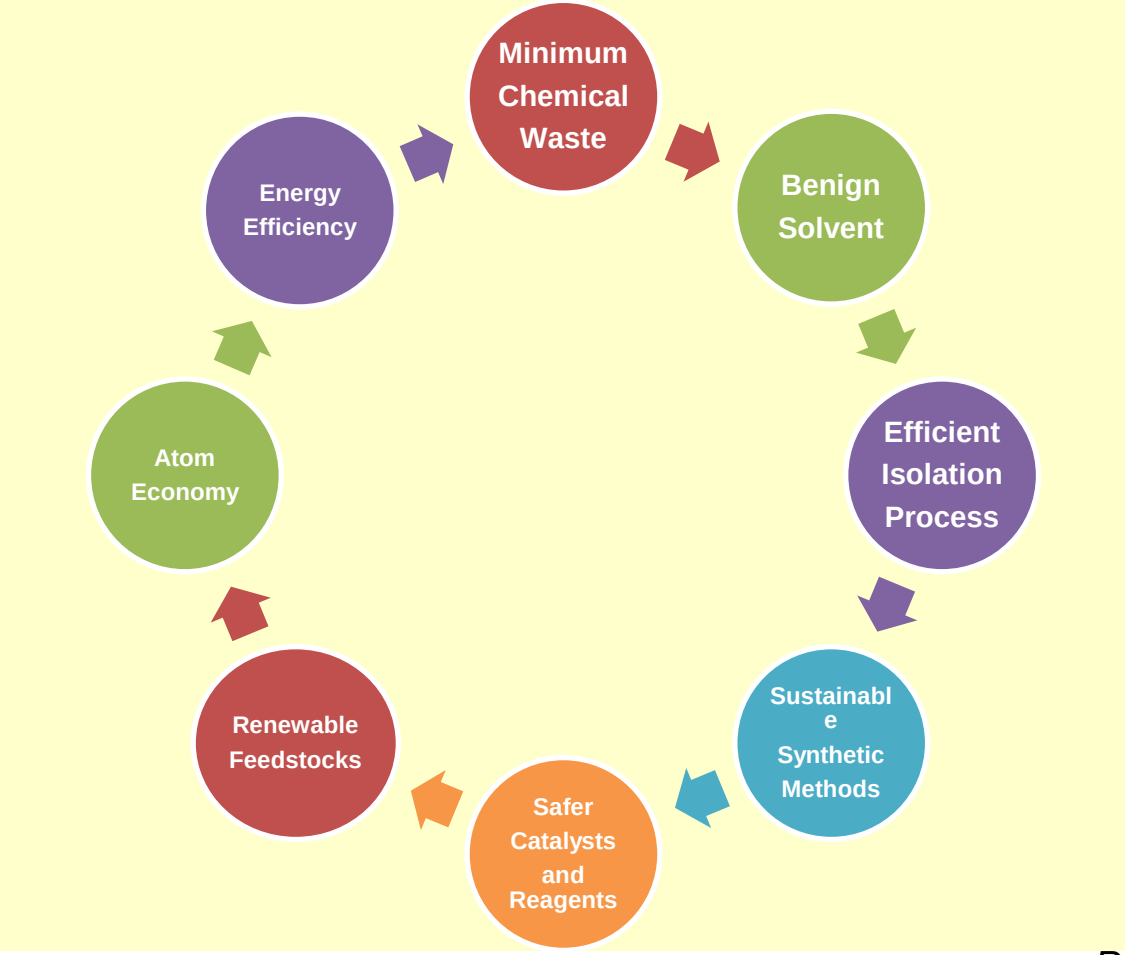
2000



2009



GREEN CHEMISTRY
NECESSARY, BUT NOT SUFFICIENT



Matrix	Definition
E Factor	Kg waste per kg product
Process Mass Intensity	Kg raw materials input vs Kg product output
Carbon Efficiency	Amount of C in product against total C in reactants
Atom Economy	How much of the atoms in the reactants are conserved in the product

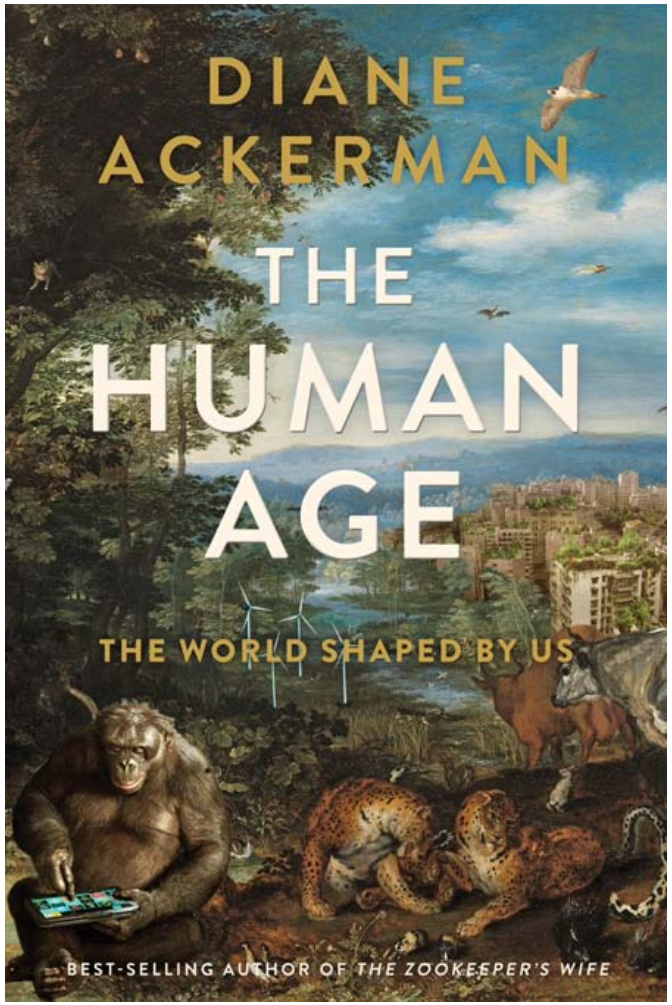
Roger Sheldon, Chem Ind.,1992, 1997
B.M. Trost, Angew. Chem. Int. Ed., 1995

GREEN, ENVIRONMENTALLY BENIGN, SAFE AND SUSTAINABLE CHEMISTRY

- Processes must be “green” and adhere to “Principles of Green Chemistry”
- Chemistry must have least impact on environment
- Chemistry must be safe to practice in the intended scale
- It must produce products which are economically viable and affordable in the intended markets
- The processes and products must fulfill the “sustainability metrics” throughout the process and product life cycle

THE HUMAN ANTHROPOCENE AGE

- Humans are leaving an indelible imprint on Planet Earth
  - Carbon cycle
  - Nitrogen cycle
  - Ocean pH
  - Extinction rate of species and habitats
- Human ingenuity and innovation capacity is also at an all time high
- However, emergence of technology alone is no guarantee that its benefit will tickle down to humanity at large.



CHALLENGES TO SUSTAINABILITY

- Population and Earth's carrying capacity
- Irreversible changes in global climate
- Providing enough food for the people
- Depletion of earth resources
- Adequate and equitable access to clean energy
- Increasing environmental contamination with persistent pollutants

SUSTAINABLE CHEMICAL INDUSTRY

- Promote responsible manufacturing
- Promote responsible consumption

How do we balance the two?
Is market the only tool to drive development ?

SUSTAINABLE CHEMISTRY : A BUSINESS VIEWPOINT

- Products used in environmental applications
- Products used to improve resource efficiency
- Products used in high technology materials
- Products made from renewable or recycled raw materials
- Products that have inherently low toxicity or ecological footprint

Sustainability is a well defined and most spoken term but difficult to comprehend and translate into action

MULTIPLICITY OF METRICS: A CAUSE FOR CONCERN

- Carbon efficiency, Reaction mass efficiency, Material efficiency , Environment quotients, Process mass intensity, etc.
- Energy footprint and energy efficiency including supply chain
- Carbon and Water footprint
- Waste footprint including end of life regeneration/ definition of grave
- Land use and changes in land use pattern
- Product safety guidelines, in use and after use
- Sustainable packaging guidelines
- Regulatory compliance such as REACH (carcinogen, mutagen, reproductive toxin)
- Tiered protocol for endocrine disruptors (TiPED)
- Fast life cycle assessment for synthetic chemistry (FLASC)
- Human rights compliance guidelines (labor, gender etc.)

R. A. Sheldon, Catalysis Today, 2015 ; R. Rajagopal, Chemical Weekly, September 2015

MULTIPLICITY OF METRICS: A CAUSE FOR CONCERN

- Green Chemistry metrics
- Green Score (Newsweek)
- USDA Bio based Product Certification
- Dow Jones Sustainability Index
- Together for Sustainability (TfS)
- EPA Environmental Technology Verification
- BEES Life Cycle Assessment
- Framework for strategic sustainable development (FSSD)

SUSTAINABILITY METRICS

- Sustainability metrics needs to be assessed across product life, value and supply chain; very often enough data is not available to perfom such analysis
- Branding chemistry “green or sustainable” in the absence of a transparent and evidence based comprehensive measurement system,commonly understood by all the stakeholders, is harmful to chemistry
- Unfortunately, there are many shades of “Green”” and some of them are “Grey”

Are papers published in peer reviewed journals such as Green Chemistry (RSC) and Sustainable Chemistry and Engineering (ACS) comply with the commonly understood definitions of “green” and “sustainable” ?

WHAT DOES THE CONSUMER NEED?

- Is the product I am using “safe” for me ?
- Is the product I am using made with the lowest impact on the resources of the planet ?
- What will happen to this product after my “use”? Where will it end up finally ?

Unfortunately, the plethora of metrics fails to address the above three simple concerns of the consumer clearly and unequivocally

THE RUSH TO RENEWABLES

- Shift from fossil fuel derived feed-stocks to renewables is often assumed as an axiom of Green Chemistry
- However, all bio derived feed-stocks are not necessarily Green !

LAW OF UNINTENDED CONSEQUENCES

April 7, 2008

Using land to grow crops for fuels and chemicals lead to destruction of forests, wetlands and grasslands that store enormous amount of carbon

Corn diverted to fuel ethanol in USA

↓

Soyabean growers switch to corn in USA

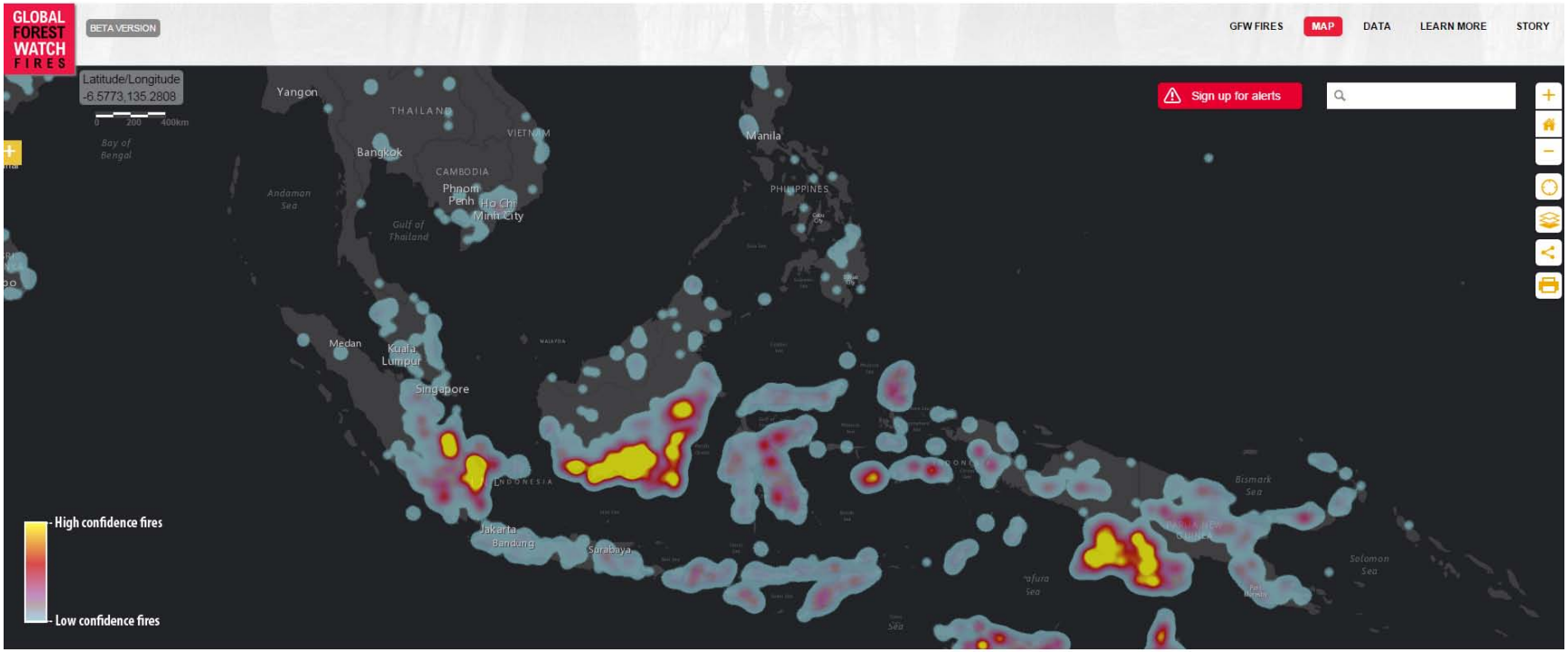
↓

Farmers in Brazil plant soyabean in land previously used as cattle pasture lands

↓

Leads to clearing of forest lands in Amazon rain forest

INDONESIA FIRES CONCENTRATED IN SUMATRA, KALIMANTAN AND PAPUA



fires.globalforestwatch.org

WORLD RESOURCES INSTITUTE

Ulet Ifansasti via Getty Images

RENEWABLE RAW MATERIALS AND THE FAR EASTERN HAZE

	% Total Land Area	% Fire detected on that land
Palm oil	7.9	12.6
Pulp wood	6.2	18.7
Logging	14.4	5.5
Moratorium	33.4	30
Others	38.1	33

- Each year vast tracts of land are set alight to clear the way for the production of Palm oil. The government imposed a moratorium in 2011 to protect 43m hectares of forest and peatlands, but fires still occur in these areas
- Palm oil is often regarded as a “sustainable renewable raw material” by the chemical industry ; Responsible and Sustainable Palm Oil Initiative (RSPO) : Sustainable supply chain option
- Carbon dioxide emissions from Indonesian forest fires exceed the annual emissions of major economies such as UK and Japan

The Guardian, 1 December 2015

IS CHEMISTRY DOOMED FOR UNINTENDED CONSEQUENCES ?

- Dow Corning, Hooker Chemicals DuPont, Freedom Industries and others followed extant prevalent rules regarding safety and environment, but were not immune to accidents or liabilities
- Unintended consequences of chemistry is always wisdom in hindsight
- Advances in biology and the tools available to assess the effect of chemicals on human and mammalian life are providing new insights on the anthropogenic chemicals use and exposures; New heuristics are emerging to prioritize human exposure to chemicals(e.g Wambaugh et al, Env. Sci. Tech.,2014)
- If so, is there an approach to "redesign" chemistry to avoid the unintended consequences and protect the future?

CLEAN AND RENEWABLE ENERGY

- In our quest to reduce the green house gas emissions, there is a haste in shifting to renewable solar energy based on photovoltaics and electric vehicles for mobility.
- These decisions have long term consequences, in the sense that , infrastructure will get locked in for centuries and shifting to alternatives will be as difficult or impossible
- So all shifts in energy technologies should be based on careful consideration of long term sustainability of material availability and the technology needed to convert the material as found in nature to devices that will power our future
- Regrettably, such analysis is sadly lacking and decisions are being made based on insufficient information

Should we be concerned about "unintended consequences" of such decisions?

IS SILICON PV GREEN ENERGY ?

Consider the following facts

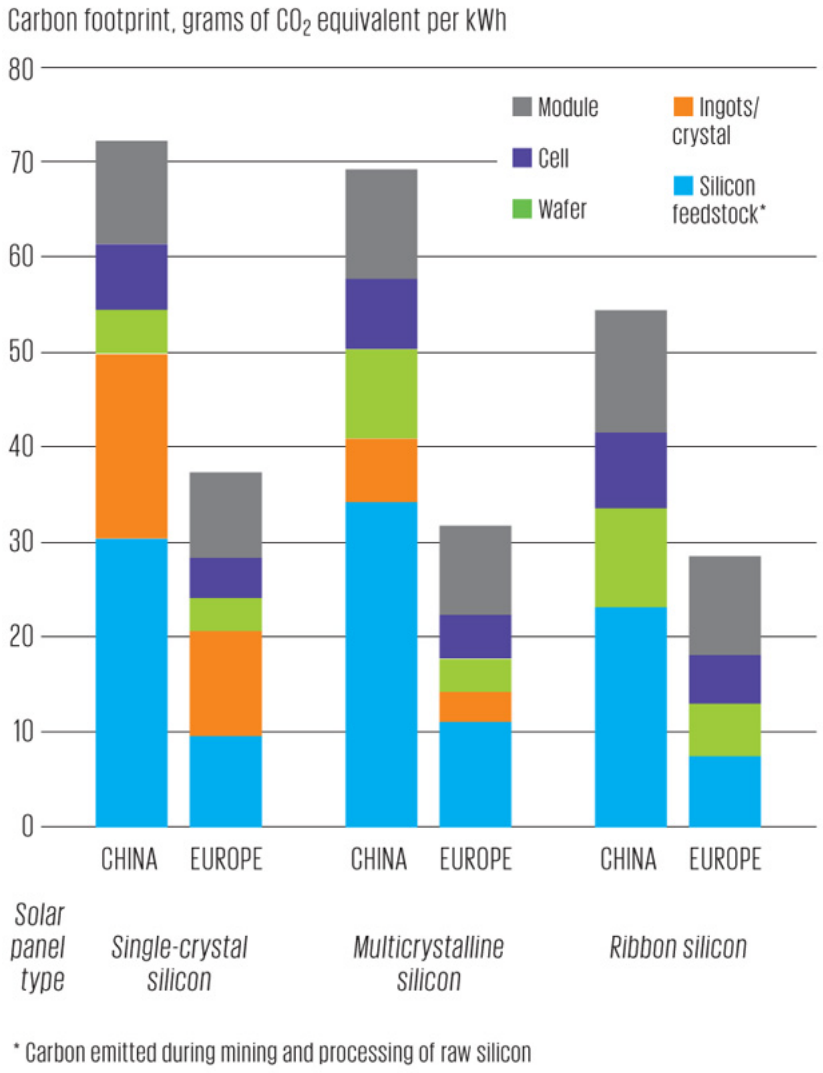
- Solar PV manufacturing processes involve converting quartz to metallurgical grade silicon and then to polysilicon ingots which are sliced to form wafers
- Every ton of metallurgical grade silicon production results in 4 tons of silicon tetrachloride.
- Material utilization efficiency is a mere 30% !
- Solar cell fabricated with Siemen's process needs six years of operation to recover the energy used to make the cells ! The enormous energy used for producing solar grade silicon comes from coal based power plants
- 1 ton of crude silicon production results in 10 t of carbon dioxide; purification process to solar grade silicon results in additional 45 t of carbon dioxide

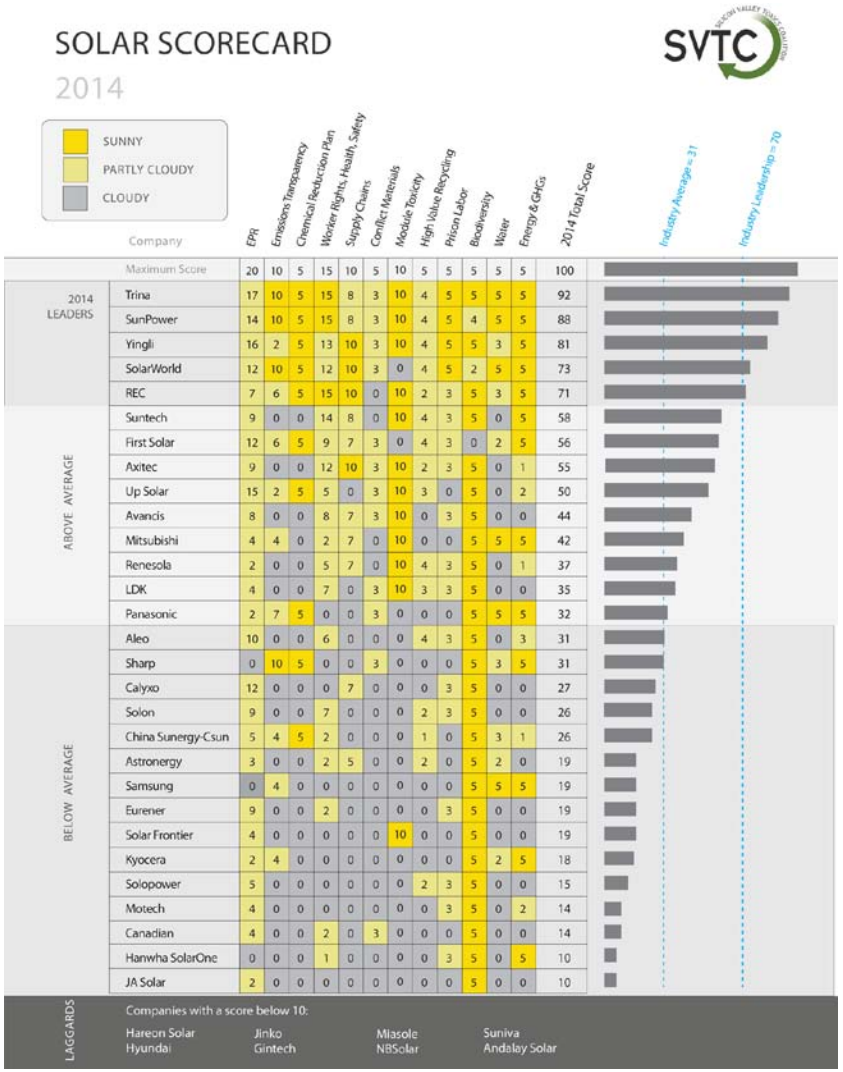
IS SILICON PV GREEN ENERGY ?

- Silicon production uses sulfur hexafluoride, HF, 1,1,1 trichloroethane and large quantities of strong acids
- Silver that is used for making panels at 5 % of current power demand will consume 50 % of the current silver produced
- Little or no recycling of silicon in-process waste or end of life panels
- Very limited data available to perform a LCA of the solar PV Silicon process

Ironic that we consider silicon PV as a clean and sustainable form of energy ! The process for manufacturing silicon will fail every rule of Green Chemistry

SUSTAINABILITY METRICS FOR SOLAR PV

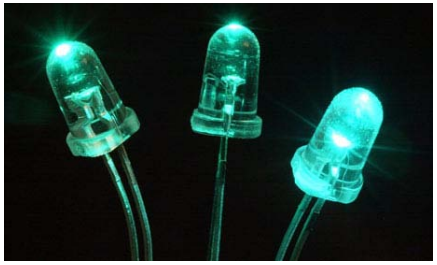




NEW MATERIALS FOR CLEAN TECHNOLOGIES

Many of the elements are either toxic or too little is available on earth. Will our dependence on them be sustainable?

- *Energy*
  - Perovskites : Lead
  - CIGS : Indium and Selenium
  - Cd/Te : Cadmium
  - Wind : Neodimium



- *Lighting*
  - LED : Gallium, Indium
- *Electric Mobility*
  - Batteries : Lithium / Neodimium

In certain areas infrastructure once created, is difficult to dismantle; therefore, material choices must be made with caution

HOW DO WE DESIGN "NEXT GENERATION" CHEMISTRY APPLICATIONS?

- Product and process design for safety and sustainability
- Chemistry that is desirable, not feasible
- Ground-up solution, not modifying existing chemistry
- Future choices of technology, processes and products must be based on a comprehensive analysis of sustainability and LCA
- Define product value as a tangible cost (raw material, energy, manufacturing, waste disposal etc.) and an intangible cost (cost on impact on the environment and sustainability discounted over the product life cycle) to reflect the true product value
- Proactive , rather than reactive to potential consequences
- Invest in deeper understanding the interface of chemistry with biology
- Improve public communication; full voluntary disclosure of every chemical used in a product may be desirable

CHEMISTRY : CENTRAL SCIENCE

- **Central to the sustenance of civilization on earth**
- **Key to management of resources on this planet**
- **Key to understanding the mysteries of life**

Chemistry is the science of the real world; the world today is searching for innovative solutions for many of its vexing problems. Chemistry must become part of this solution and dispel the image that it is the cause of the problem

THE FUTURE OF CHEMISTRY

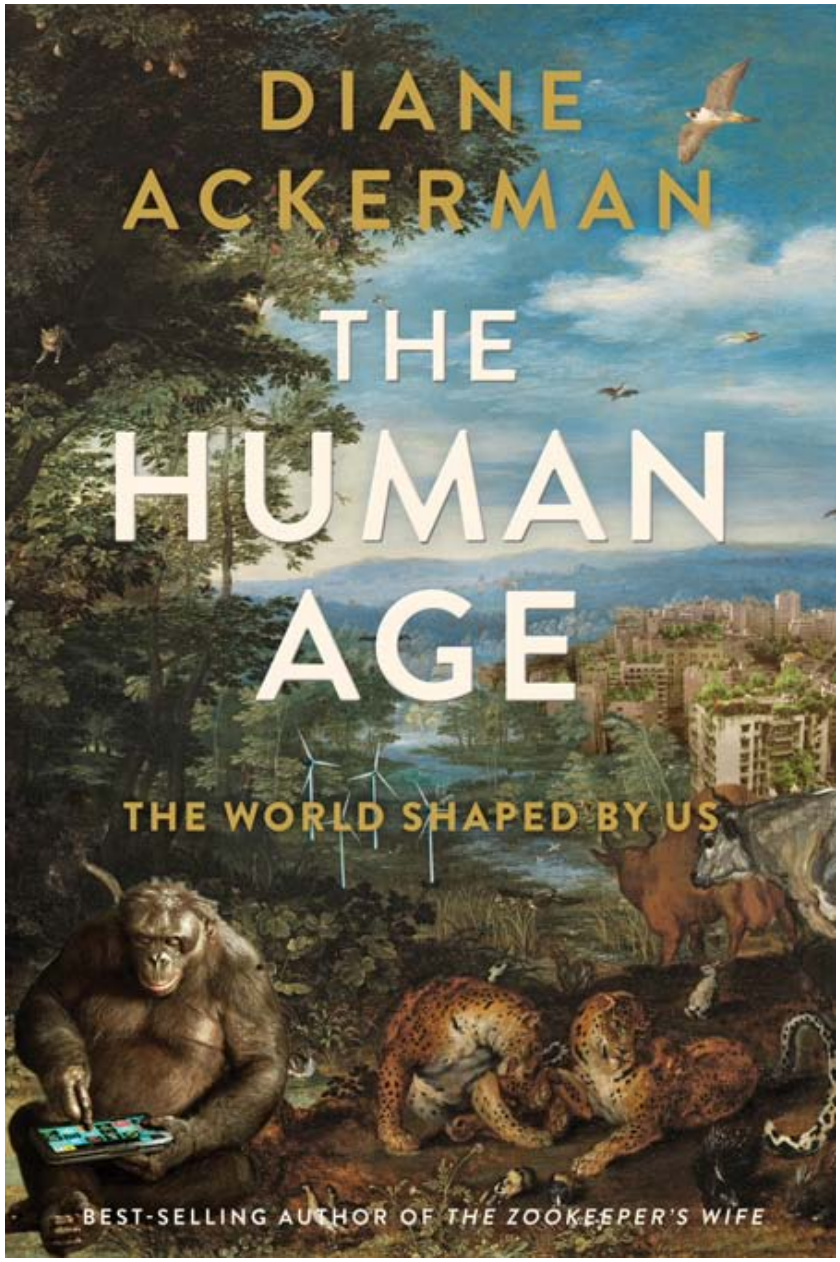
“ Chemistry, by its very culture has been blindly reductionist. I am often reminded that chemists work on molecules, but they must also work on problems where molecules may be only part of a solution. We think of ourselves as experts in quarrying blocks from granite; we have not thought it our job to build cathedrals from them ”

George M. Whitesides, Angew. Chem. Intl. Ed., 2004

For chemistry to become sustainable, we have to move from a reductionist thinking to a system based thinking; from “bottoms up” design to” top down” understanding

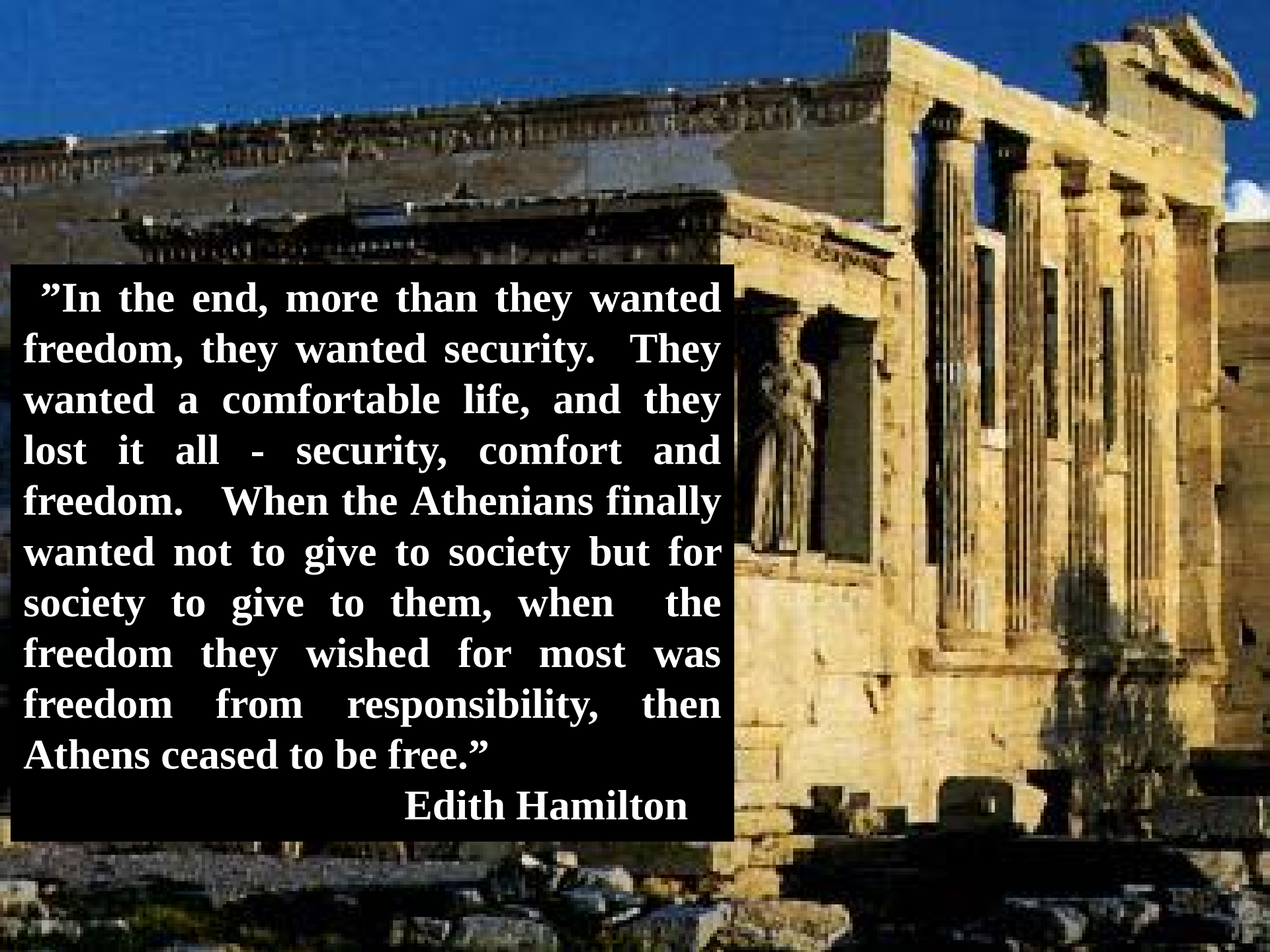
Unless green chemistry, safety, affordability and sustainability are deeply embedded in the practice of chemistry and industry, we may not be able to rescue chemistry from the already fragile public perceptions

- ✓ We need to communicate to our stakeholders that chemistry is a responsible science
- ✓ If we fail to do this, the only favorable public gaze of chemistry will be in our shopping malls !



Our relationship with nature has changed radically, irreversibly, but by no means all for the bad. Our new epoch is laced with invention. Our mistakes are legion, but our talent is immeasurable."

Diane Ackerman,
The Human Age



”In the end, more than they wanted freedom, they wanted security. They wanted a comfortable life, and they lost it all - security, comfort and freedom. When the Athenians finally wanted not to give to society but for society to give to them, when the freedom they wished for most was freedom from responsibility, then Athens ceased to be free.”

Edith Hamilton

THANK YOU