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**GREEN  
CHEMISTRY**



# ACCIDENTS AND UNINTENDED CONSEQUENCES



Image: Wikimedia Commons, Quai Paul Riquet (embankment) in Sète, Hérault, France, Author: Christian Ferrer

**DAY 1 SESSION II**  
**4-DAY PRESENTATION**

[www.greenchemistry-toolkit.org](http://www.greenchemistry-toolkit.org)



## Topics To Be Covered

1. Chemical and Industrial Accidents
  - Union Carbide, 1984
  - Cuyahoga River, 1969
  - Port of Tianjin, 2015
2. Unintended Consequences
3. Green Chemistry is Everybody's Job
4. Perspective and Context
5. Green Chemistry – Where do we go from here?

# INDUSTRIAL AND CHEMICAL ACCIDENTS

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Aftermath of infrastructure damage

1. What do you see?
2. What do you think happened?



<https://www.theatlantic.com/photo/2014/12/bhopal-the-worlds-worst-industrial-disaster-30-years-later/100864/>

[www.thankallasingh.org](http://www.thankallasingh.org)



Poison gas leaked from a Union Carbide factory (Bhopal, India), killing thousands of people instantaneously, and injuring many more (many of whom died later of exposure). Up to **20,000** people have died as a result of exposure (3-8,000 immediately after). More than **120,000** still suffer from ailments caused by exposure.

## How did this happen?

- Methyl isocyanate – used to make pesticides was being stored in large quantities on-site at the plant.
- Methyl isocyanate is a highly reactive, exothermic molecule.
- Most safety systems either failed or were inoperative.
- Water was released into the tank holding the methyl isocyanate.
- The reaction occurred and the methyl isocyanate rapidly boiled, producing large quantities of toxic gas.

# UNION CARBIDE, 1984

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Flare tower where toxic methyl isocyanate gas was released into the air.

What is left of the abandoned Union Carbide plant.



<https://www.theatlantic.com/photo/2014/12/bhopal-the-worlds-worst-industrial-disaster-30-years-later/100864/>



# CUYAHOGA RIVER – CLEVELAND, OHIO, 1969



There were many things being dumped in the river such as: gasoline, oil, paint, and metals. The river was called "a rainbow of many different colors."

Fires erupted on the river several times before June 22, 1969, when a river fire captured national attention when Time Magazine reported it.



Some river! Chocolate-brown, oily, bubbling with subsurface gases, it oozes rather than flows. "Anyone who falls into the Cuyahoga does not drown," Cleveland's citizens joke grimly. "He decays."

- Time Magazine, August 1969



# CUYAHOGA RIVER – CLEVELAND, OHIO, 1969

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Images Courtesy of The Cleveland Press Collection, Cleveland State University Library; Author: Fred Bottomer, and James Thomas



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[www.rhemkallensind.org](http://www.rhemkallensind.org)

A series of explosions killed 173 people and injured hundreds of others at a container storage station.

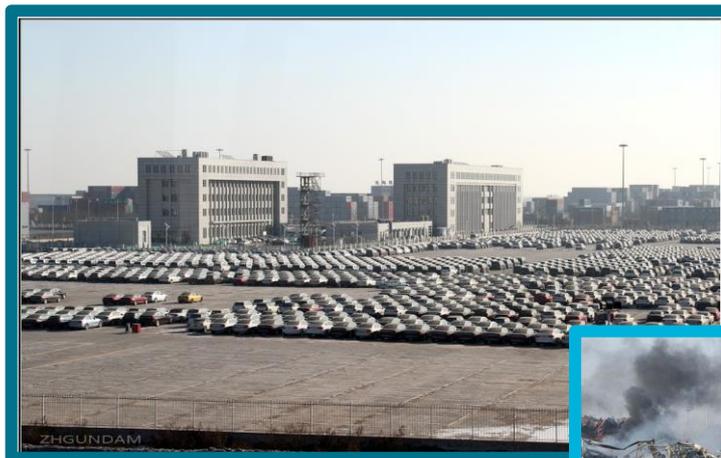
The first two explosions occurred within 30 seconds of each other at the facility. The second explosion was far larger and involved the detonation of about 800 tons of ammonium nitrate. Fires caused by the initial explosions continued to burn uncontrolled throughout the weekend, repeatedly causing eight additional secondary explosions.

The facility stored large quantities of sodium cyanide and calcium carbide, as well as 800 tons of ammonium nitrate, which is principally used in manufacturing fertilizer.

In total, 304 buildings, 12,428 cars, and 7,533 intermodal containers were damaged.

The cost of damage was estimated at \$9 billion.

# PORT OF TIANJIN, 2015



Before



After

<https://sploid.gizmodo.com/photos-from-the-devastating-aftermath-of-the-tianjin-ex-1723899654>



# PORT OF TIANJIN, 2015



<https://www.nytimes.com/2015/08/21/world/asia/cyanide-levels-tianjin-china-explosion.html>  
<http://www.radionacional.com.pe/sites/default/files/noticias/explosion%20tianjin.jpg>

[www.rhemikallasid.org](http://www.rhemikallasid.org)



# TOP FIVE CHEMICALS INVOLVED IN ACCIDENTS WITH INJURIES (2008)

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**Carbon monoxide (2,364 accidents):** This colorless and odorless gas lurks silently and cause minor symptoms, such as headache and dizziness, or even sudden death. Many of the accidents in the CDC study involving CO happened at private homes. Of the five listed chemicals, CO had the highest rate of fatalities.

**Ammonia (1,153):** Ammonia can also cause sudden death. More that half of the accidents involving this colorless gas happened in agriculture, where it is applied directly on soil, and in food manufacturing plants, where it is used as a refrigerant.

**Chlorine (783):** Chlorine is a vital industrial chemical used to produce a wide range of products, including vinyl chloride, plastics, aerosols, silicone, and foam. Most of the recorded injuries happened at paper and printing manufacturing facilities and at swimming pools.

**Hydrochloric acid (326):** Used to manufacture fertilizers, dyes and rubber, hydrochloric acid is highly corrosive to human skin. Most of the reports involving hydrochloric acid happened in warehousing and transportation.

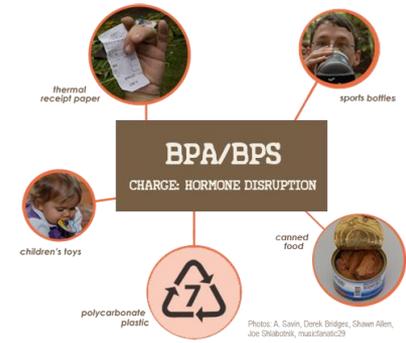
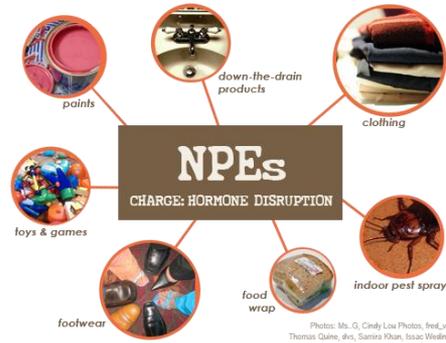
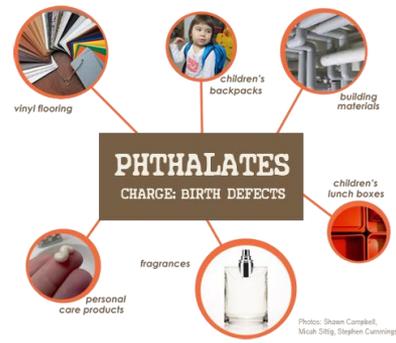
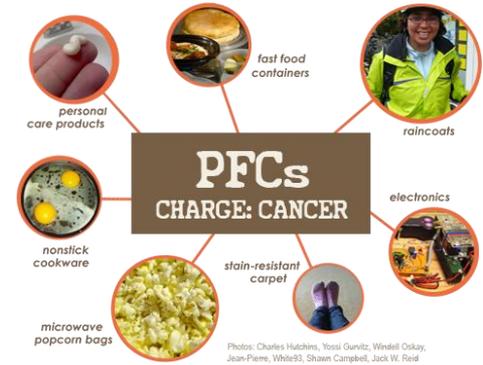
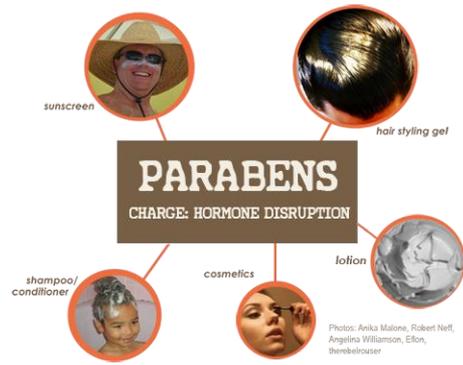
**Sulfuric acid (318):** Another corrosive substance, sulfuric acid is used to make explosives, glue, other acids, and used to purify petroleum and in the picking of metal. A high percentage of recorded incidents with sulfuric acid involved equipment failure.

<https://www.chem.info/article/2016/06/top-5-chemicals-involved-injury-causing-accidents>



# CONSUMER PRODUCTS

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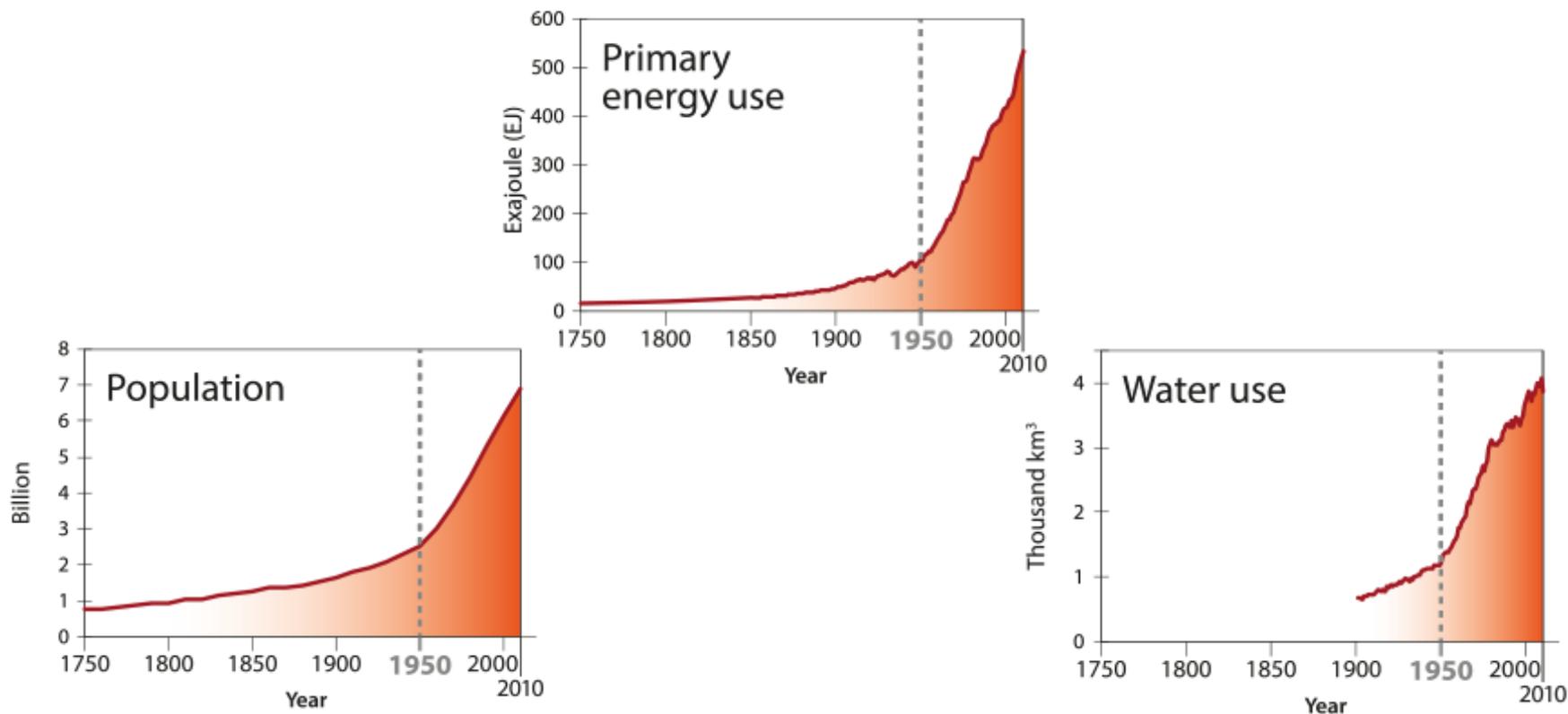


www.thankalliance.org



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# UNINTENDED CONSEQUENCES – INDUSTRIAL ERA

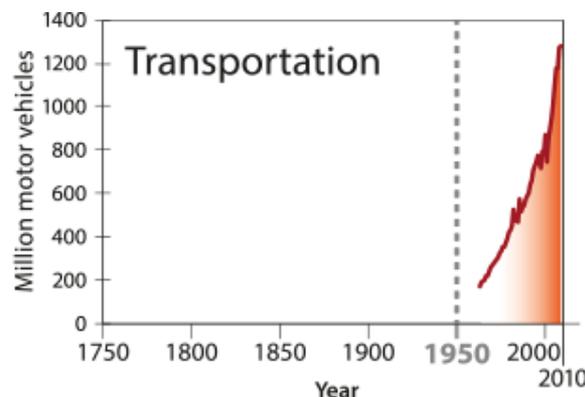
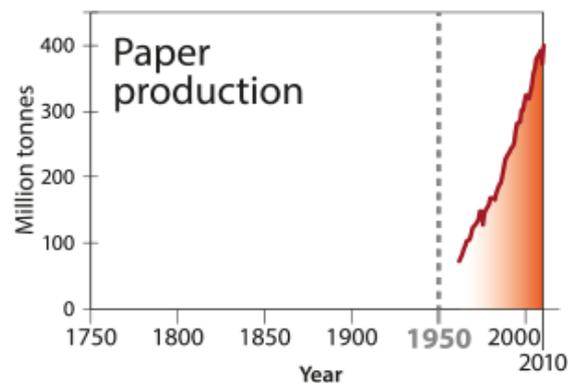


Steffen *et al.* The trajectory of the Anthropocene: The Great Acceleration (*Anthropocene Review*) 16 January 2015. Design: Globaia

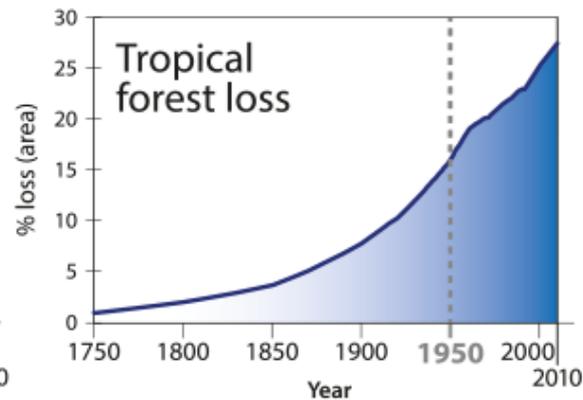
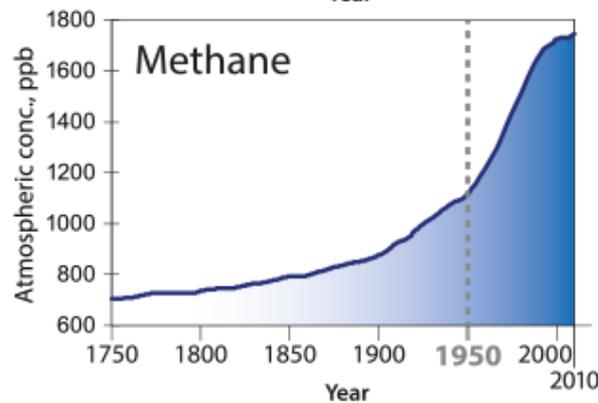
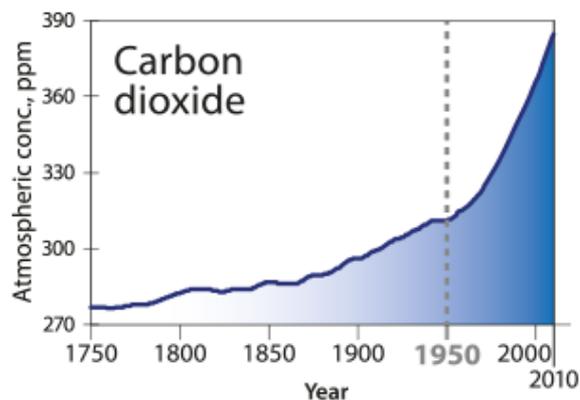


# UNINTENDED CONSEQUENCES – INDUSTRIAL ERA

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With an increasing population, the need for resources is even greater – which negatively impacts the environment.



Steffen *et al.* The trajectory of the Anthropocene: The Great Acceleration (*Anthropocene Review*) 16 January 2015. Design: Globaia





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**We've tried to fix some of these  
problems, but ended up doing the right  
thing in the wrong way.**

# MORE UNINTENDED CONSEQUENCES



Biofuels made from corn that compete with food, livestock feed, and land use.



Image source: Adobe Stock

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# MORE UNINTENDED CONSEQUENCES



Purifying water with acutely lethal substances.

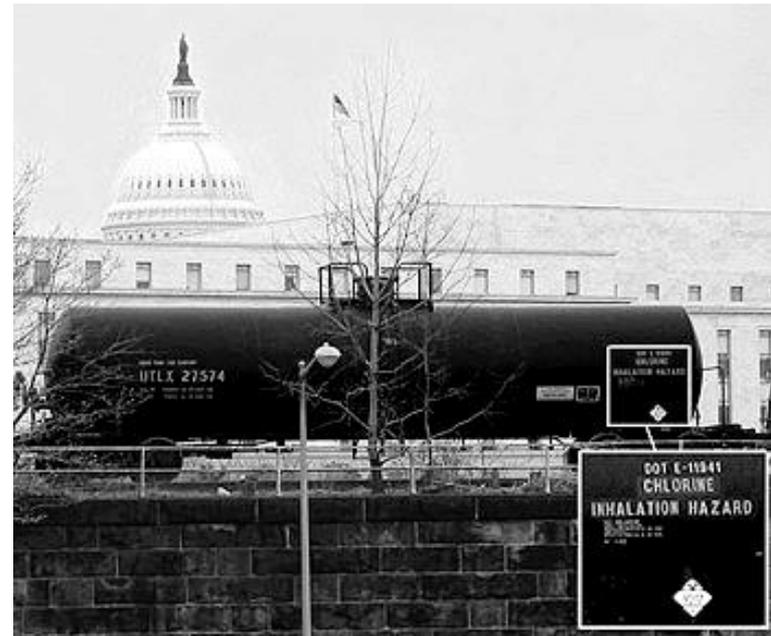


Image Source: <http://jimdougherty.net/misc/>

Chlorine transported in Washington D.C.

# MORE UNINTENDED CONSEQUENCES

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Renewable energy through the  
use of precious, rare, toxic  
metals in photovoltaics.



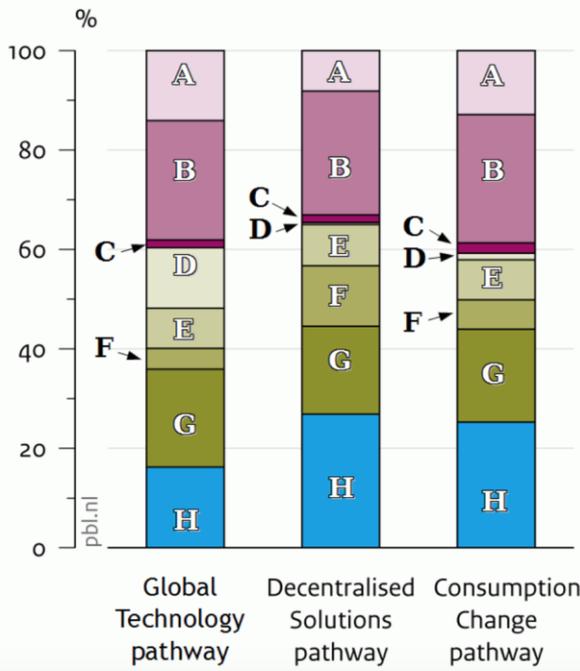
Image source: Wikipedia

Solar panel installed on the roof of the building.



# IN ORDER TO GO FORWARD, WE NEED MORE SUSTAINABLE ACTIONS.

Contribution to cumulative emission reduction, 2010 – 2050



- A**  Avoid deforestation
- B**  Reduce other greenhouse gases
- C**  Reduce other energy-related emissions
- D**  Increase nuclear power
- E**  Increase bio-energy
- F**  Increase solar and wind power
- G**  Increase CO<sub>2</sub> capture and storage
- H**  Improve energy efficiency



**All of these solutions involve the 12 Principles of Green Chemistry**

[https://commons.wikimedia.org/wiki/File:Limiting\\_global\\_warming\\_to\\_2\\_degrees\\_Celsius\\_-\\_options\\_to\\_reduce\\_greenhouse\\_gas\\_emissions\\_\(PBL\).png](https://commons.wikimedia.org/wiki/File:Limiting_global_warming_to_2_degrees_Celsius_-_options_to_reduce_greenhouse_gas_emissions_(PBL).png)

# WHY DO GREEN CHEMISTRY?

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“It’s not my job...”



Image source: Pixnio, Author: Amanda Mills, USCDCP

[www.fhmkalliance.org](http://www.fhmkalliance.org)



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# CHEFS

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Image source: Wikipedia, Author: MMS

The meals I make are delicious!

Sure, they're poisonous.

But there are **other** chefs working on “non-lethal cooking”.

[www.greenchemistry.org](http://www.greenchemistry.org)



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# ARCHITECTS



The homes I've built are luxurious and attractive. Sure, they collapse and kill people on a regular basis. But there are **other** builders who are working on "safe housing."



Image source: Wikimedia Commons, Author: Auburn University College of Architecture, Design and Construction



# CAR DESIGNERS

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Image source: Flickr, Author: Thomas Bersy

I build the fastest and most beautiful cars in the world. Sure, they often fall apart and explode unexpectedly. But there are **other** car designers working on “sustainable cars.”

[www.chemkollisions.org](http://www.chemkollisions.org)



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# CHEMISTS

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I've developed some of the best methodologies and processes for making hundreds of target molecules.

Sure, they harm humans and the environment.

But there are **other** chemists working on “green chemistry”.



Image source: U.S. Air Force photo by Susan A. Romano





We need to remember that fundamentally green chemistry is about redesigning the tools of our trade - the molecules, and the transformations, and the processes themselves.

The fact that even today the vast majority of chemists and chemical engineers are generally and fundamentally unaware of the inherent nature and the consequences of the molecules we use or make is an important condemnation of our chemistry community and an important challenge to us to ensure that it is changed.



Carl Wilhelm Scheele.

Carl Scheele - discoverer of fluorine, chlorine (credited to Humphrey Davy), manganese, barium, nitrogen and oxygen (credited to Priestly) - died from exposure to hydrocyanic acid.

Humphry Davy discovered a fifth of the elements known at the time. He died of overexposure to nitrous oxide.



Image source: Wikimedia Commons, Authors Unknown

# MADAME CURIE

## GREEN CHEMISTRY

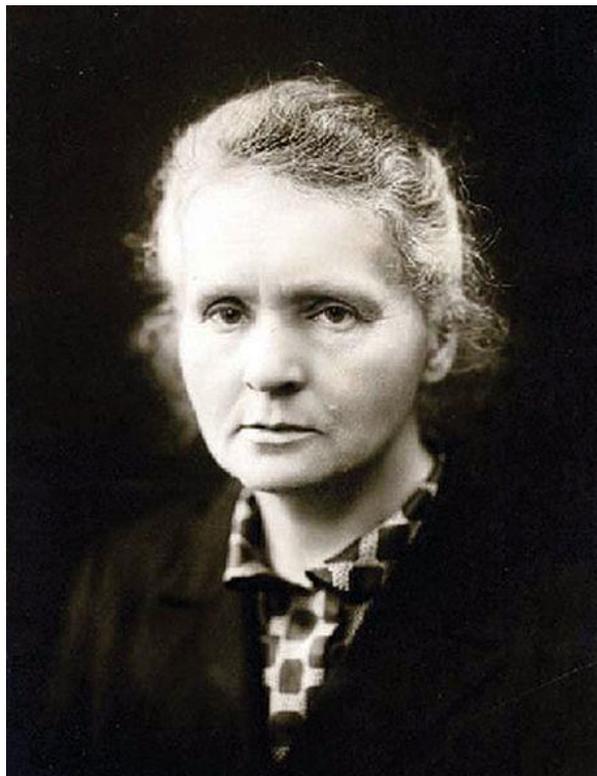


Image source: Wikimedia Commons, Author Unknown

Marie Curie, died of radiation induced leukemia a few years after receiving her Nobel Prize. Her lab notebooks from the 1890's are still kept in lead-lined boxes and people must wear protective clothing in order to view them.

It wasn't until 1938 (**less than 100 years ago**) that radioactive consumer products such as toothpaste and laxatives were banned from the market.



# ROSALIND FRANKLIN

Rosalind Franklin - co-discoverer of the structure of DNA - died due to the tools of her research at the age of 37, four years before she could receive her Nobel Prize along with Watson and Crick.

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Image source: The National Library of Medicine's Profiles in Science, Author Unknown, From the personal collection of Jenifer Glynn

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These luminaries were not careless,  
thoughtless, or stupid.

They were just working in the context  
and perspectives of their time.

There didn't yet exist an understanding  
of the molecular basis of hazard.



We would like to believe that innovation and change is the hallmark of scientific advance – it is also true that change can come much more slowly than anyone might expect.

Simply stated, people don't like to do things differently from the way they have done them before.

New ideas and new perspectives often face harsh opposition.

# LORD KELVIN

# GREEN CHEMISTRY

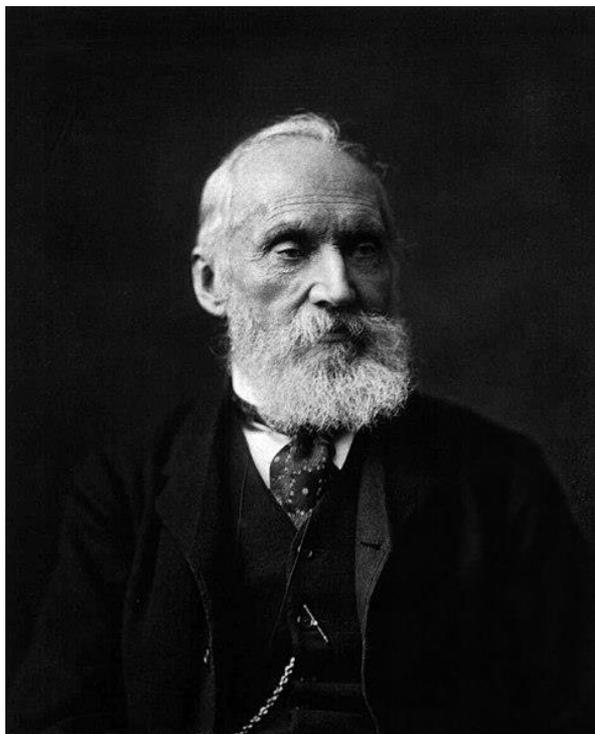


Image source: Wikimedia Commons, Author: Photo by Messrs. Dickinson, London, New Bond Street

Lord Kelvin - discoverer of the temperature scale named for him - insisted that his calculations that the Earth was only 24 million years old long after Rutherford had demonstrated this to be false by using radio isotope dating.

[www.lordkelvin.org](http://www.lordkelvin.org)



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# DMITRI MENDELEEV

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Mendeleev, inventor of the periodic table, refused to acknowledge the existence of radiation - or even of the electron.

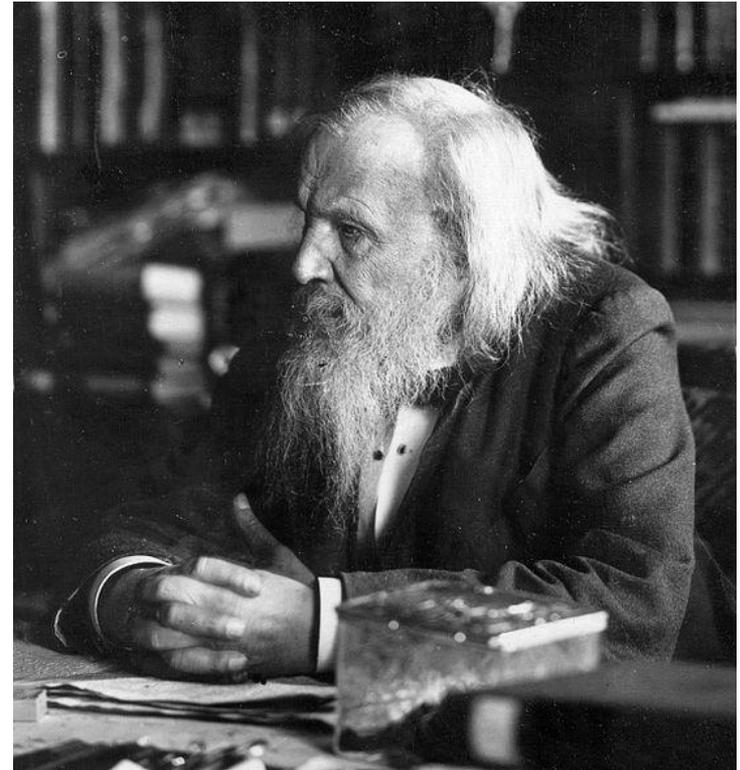


Image source: Wikimedia Commons, Author Unknown



# J.J. THOMPSON

# GREEN CHEMISTRY



Image source: Wikimedia Commons, Author Unknown

J.J. Thompson is quoted famously in defense of "ether" as "it is as essential to our lives as the air we breathe"

*(long after it was disproven)*

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# ALBERT EINSTEIN



Einstein's rejection of quantum mechanics  
“God does not play dice with the universe” is legendary.

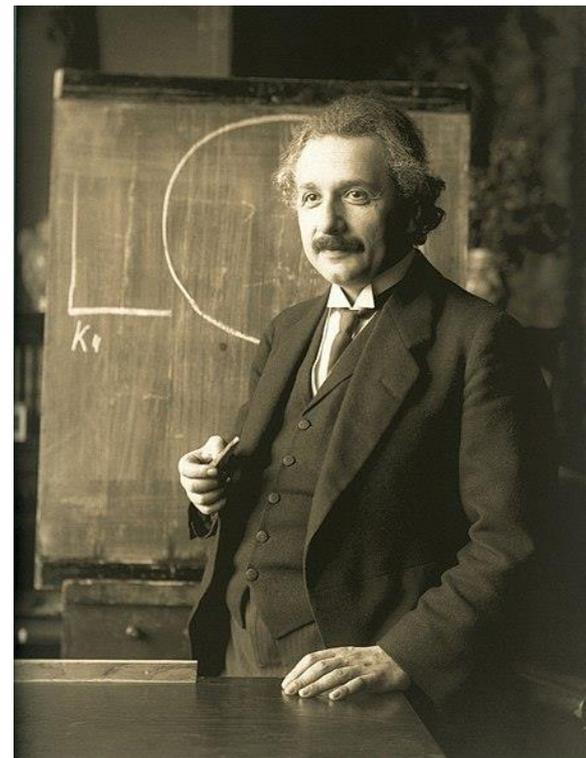


Image source: Wikimedia Commons, Author: Ferdinand Schmutzer



These cases are not meant to ridicule or demean the great scientists of the past. Exactly to the contrary. Many of them were geniuses and all of them dramatically moved science forward.

The point is that leaders in scientific thought - even those who have had great breakthroughs - do not necessarily recognize the next generation of new and innovative ideas.

# WHY IS WORKING TOWARD GREEN CHEMISTRY IMPORTANT?

## GREEN CHEMISTRY



Because it leads to **CHANGE**



Image source: <https://earthobservatory.nasa.gov/Features/OrbitsCatalog/page2.php>

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# WHAT IS GREEN CHEMISTRY?

## GREEN CHEMISTRY



“Green Chemistry is a revolutionary approach to the way that products are made; it is a science that aims to reduce or eliminate the use and/or generation of hazardous substances in the design phase of materials development”

– *John Warner, Co-Founder of Green Chemistry*

[www.hemkollensid.org](http://www.hemkollensid.org)



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# HOW DO WE PROCEED FROM HERE?

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With brilliance and optimism

Science and technology have risen to the challenge and we have the creativity and capability to do it again.

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# HOW DO WE PROCEED FROM HERE?

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## Responsibly

With power comes responsibility. With all the knowledge, perspective, and training you acquire, you also have acquired the ability to impact others – to impact the world. Once you have the power to impact the world, you have the responsibility to impact it for the better.

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# HOW DO WE PROCEED FROM HERE?

**GREEN  
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With conviction, courage, and commitment

Green Chemistry and Green Engineering

Because we can.

Because we must.

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**THANK YOU!**  
**QUESTIONS?**

This training material was developed in close collaboration with the **Center for Green Chemistry and Green Engineering** at Yale University.

[www.greenchemistry-toolkit.org](http://www.greenchemistry-toolkit.org)