International Organization for Chemical Sciences in Development

I O C D

Imperial College London
Institute of Global Health Innovation

The Chemical Sciences and a Sustainable Future

Presentation based on the TGH Jones Memorial Public Lecture
University of Queensland: 16 July 2018

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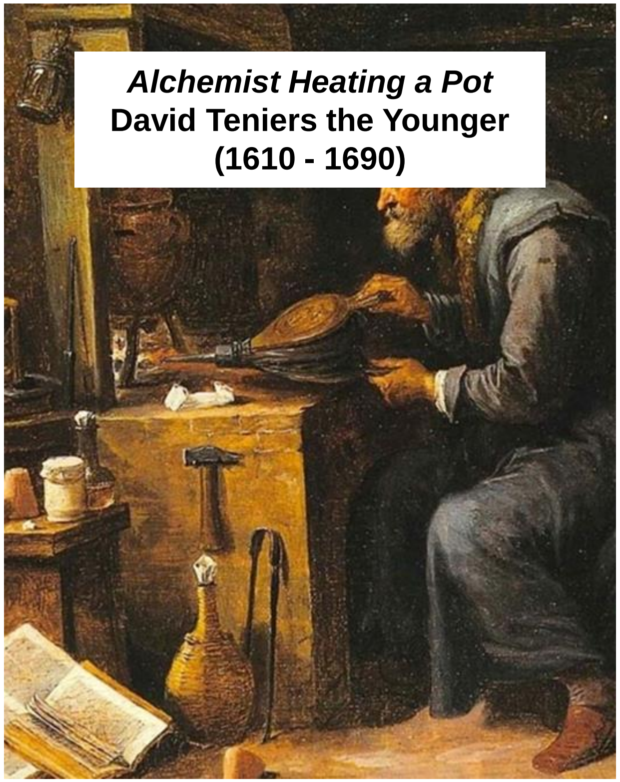
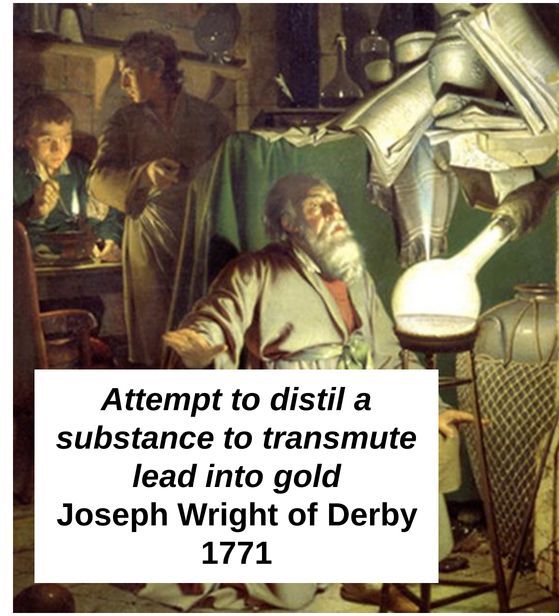


Alchemist Heating a Pot
David Teniers the Younger
(1610 - 1690)

Philosopher's Stone
for metals

Alchemy

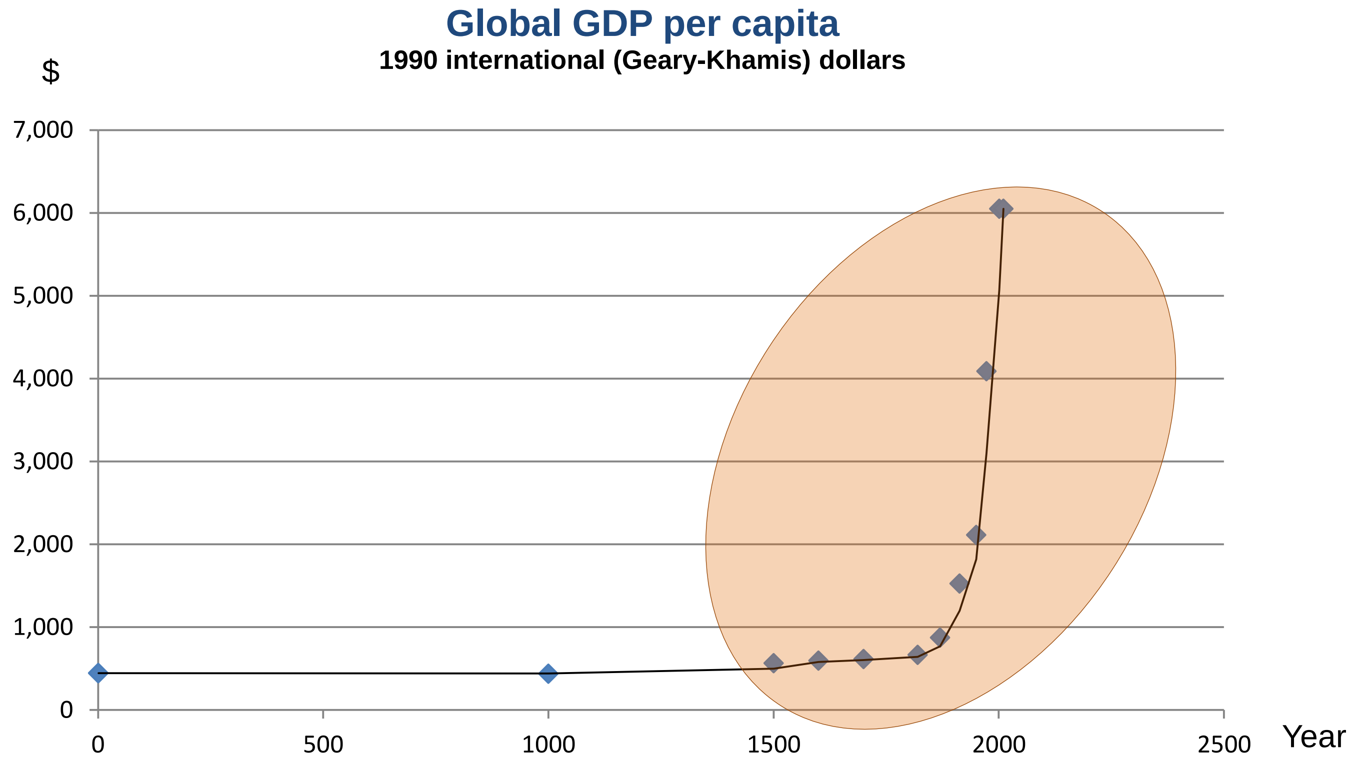
Elixir of Life
for humans



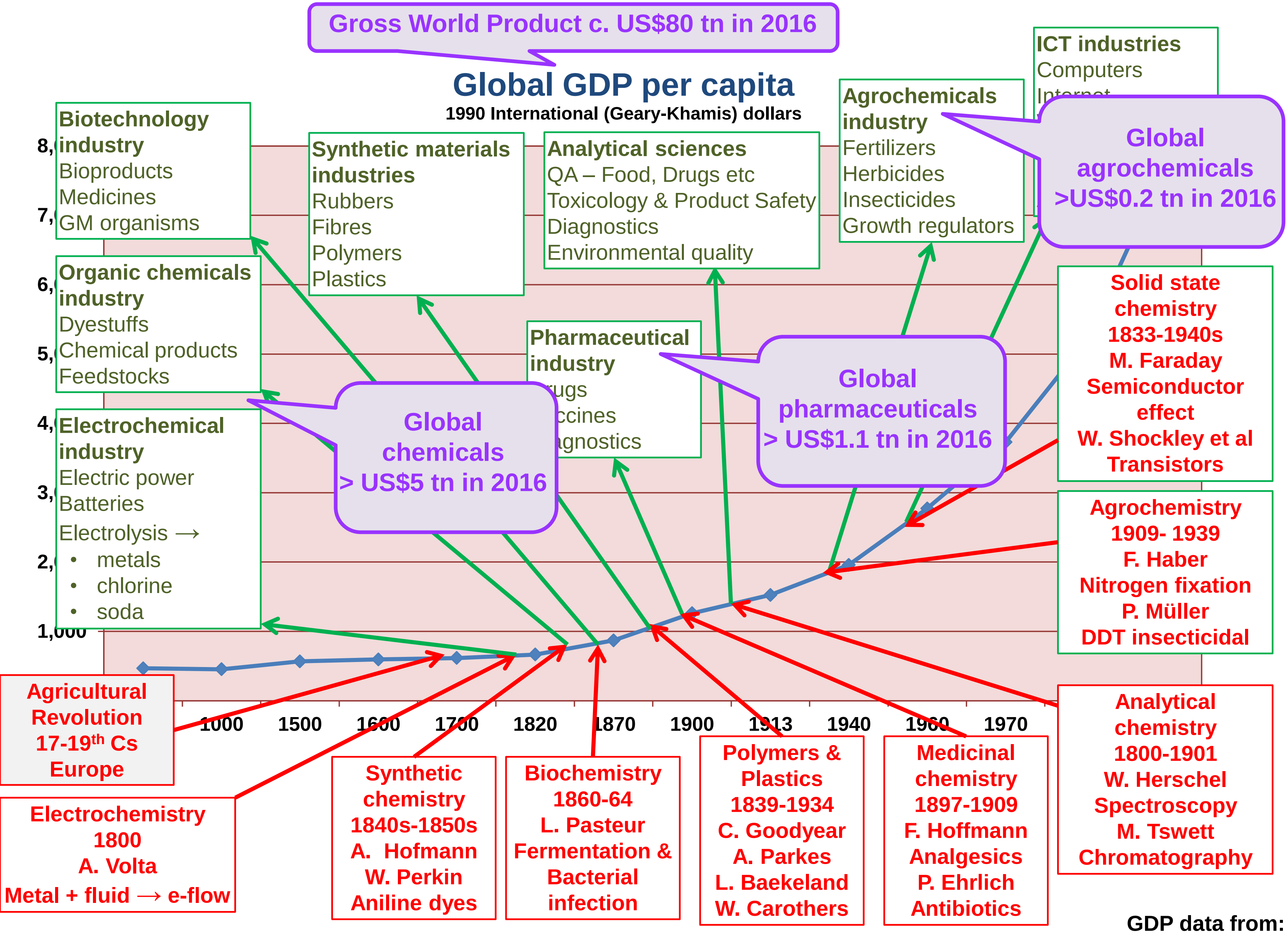
Attempt to distil a substance to transmute lead into gold
Joseph Wright of Derby
1771

Black Powder: S, C, KNO_3
probably invented by Chinese alchemists searching for *Elixir of Life*

The chemical sciences have been central to global progress (e.g. contributing to increasing wealth)



GDP data from:
A. Maddison, Statistics on World Population, GDP and Per Capita GDP, 1-2008 AD. www.ggdc.net/MADDISON/oriindex.htm



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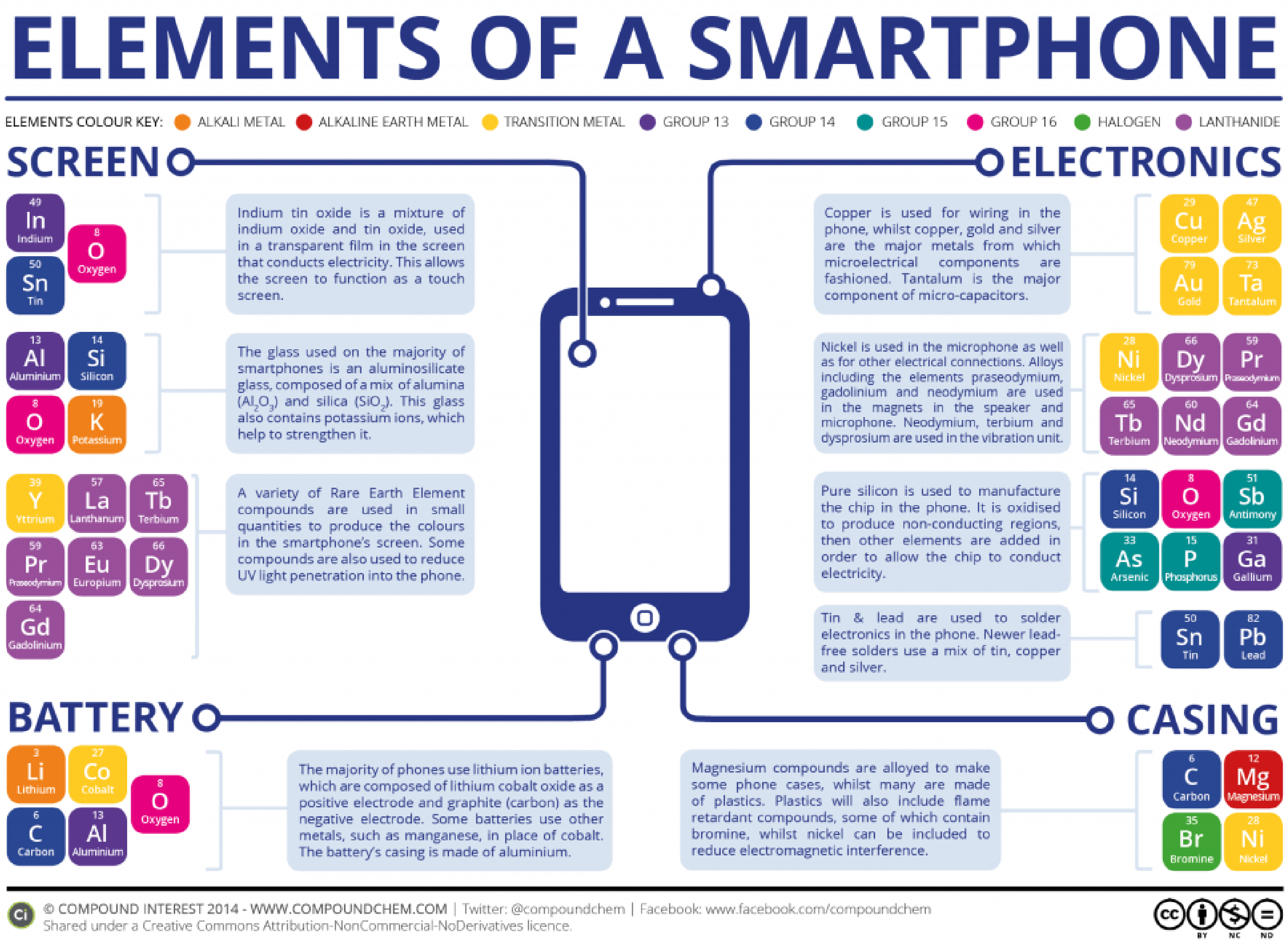
Global smartphone market >US$430 bn in 2016



Country Income Groups GDP/capita (World Bank Classification 2016)

Belgium (2015 GDP/capita US$ 40,324)

19th century

- Ernest Solvay, Lieven Gevaert, Léo Baekeland, Albert Meurice

2015 chemical industry and life sciences

- Turnover >€ 64.3 billion: 24.2% of total manufacturing sector
- Direct employment 88,700 jobs: 18.9% of all manufacturing sector employment (+ sector creates c. 150,00 indirect jobs)
- Exports: 33% of total Belgian exports; positive trade balance >€ 20 bn
- Investment €1.93 billion: 30% of total manufacturing investment
- R&D expenditure in chemical & life sciences industry €3.6 billion: nearly 60% of all private-sector R&D in Belgium

www.essenscia.be/en/our_sector

Taiwan (2015 GDP/capita US$ 22,469)

1950s: GDP/capita US$ 919

1990: GDP/capita US$ 7,358

- Chemical industry is largest industrial sector, contributing 24.2% of the total production value of US$165.3 billion (8.5% directly to export sales of US$95.6 billion).
- A leading producer of some plastics and synthetic fibres
  1. Established backwards-integrated chemical industry
  2. Developed ‘debottle-necking’ capacity
  3. Cooperation between up/mid/ downstream operators
  4. Strong support by the government

2010

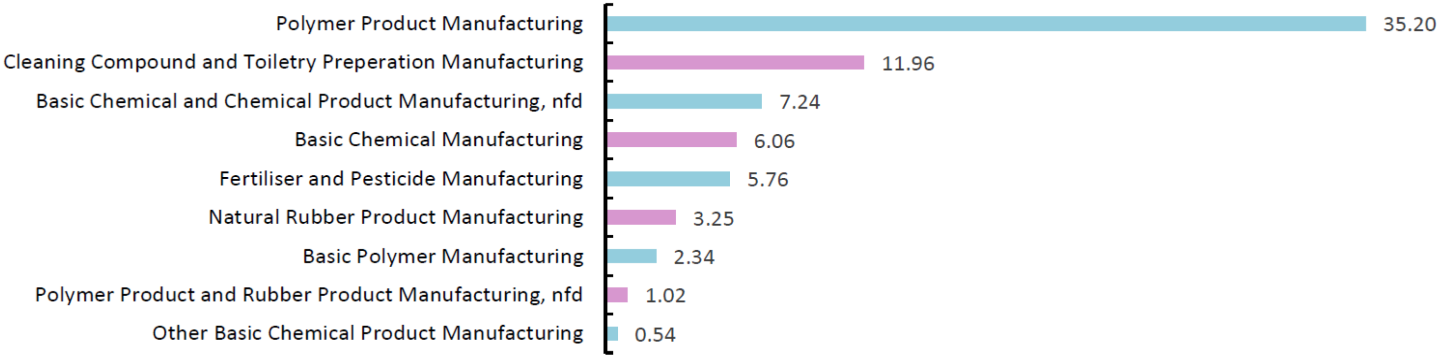
- Total revenue US$ 135 bn: 29.3% of GDP in manufacturing sector

www.aiche.org/sites/default/files/cep/20120441.pdf

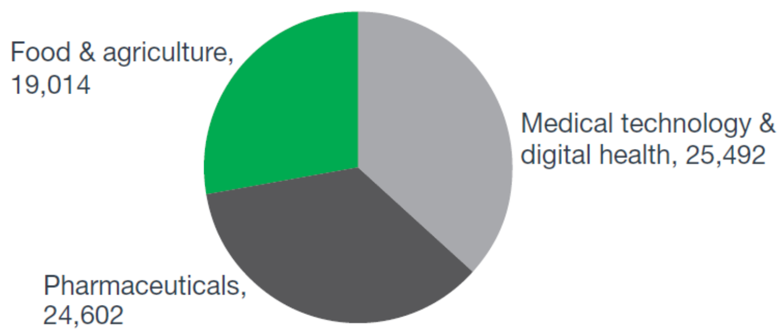
Country Income Groups GDP/capita (World Bank Classification 2016)

Australia (2015 GDP/capita US$ 51,344)

Current Employment November 2016- Chemicals and Plastics Manufacturing Group



Distribution of industry life sciences employee (number)



High ($12,736 or more)

No data

http://databank.worldbank.org/data/download/site-content/wdi/maps/world-by-income-wdi-2016.pdf

The chemical sciences have been central to global progress (e.g. contributing to increasing wealth)

Look at all the good things that chemistry has done for us!

"better living through chemistry"

The bad things are due to people, not chemistry!

- <u>**All**</u> **[chemistry] knowledge can be applied for good or bad:**
  – it's people (scientists, policy-makers, public) who decide

- **Chemistry literacy enables the capacity to make informed choices**

- **All choices have implications beyond the immediate setting:**
  – chemistry literacy must be taught in the context of real-world applications

Google

chemical-free products

£1million bounty offered for UK's first chemical-free product

23 February 2010

The Royal Society of Chemistry (RSC) has announced a £1 million bounty to the first person who can crack the impossible: create a product that the RSC considers to be 100% chemical-free.

The challenge has been set as research by the UK's cosmetic and toiletries industry reveals 52% of women and 37% of men actively seek out chemical-free products, demonstrating the deep-seated public confusion about the role and application of chemicals in daily life.

The RSC made the announcement at a media event in central London hosted by the UK's Cosmetic, Toiletry and Perfumery Association (CTPA). The event, entitled "The Facts About Chemicals", explored the popular perception of chemicals as something harmful to be avoided, a view shared by 84% of consumers who feel at some level concerned about the health impact of the chemicals in their everyday products.

The Chemical Sciences and a Sustainable Future

- The chemical sciences have been central to global progress (e.g. contributing to increasing wealth) (up to a point; for some) and will be essential to meeting oncoming global challenges
  - especially sustainable development
- To make its optimal contribution, chemistry must change
  - 'one-world chemistry' offers a framework
- Examples

The Chemical Sciences and a Sustainable Future

Nature of chemistry

1. **Core physical science – understanding the properties and behaviour of atoms and molecules and the transformation of substances**

2. **Provides useful applications**
   Marcellin Berthelot (1827 – 1907): ***"chemistry creates its own object"***

3. **Platform science – fundamental to the development of a range of other 'molecular sciences' which depend on knowledge of the properties, behaviour and transformations of atoms and molecules, including:**
   - **Biochemistry**
   - **Molecular biology**
   - **Materials science**
   - **Nanoscience**

   } →

   - ❑ **Medicine**
   - ❑ **Food production**
   - ❑ **Structural & functional materials**
   - ❑ **Energy & Fuels**
   - ❑ **Information & communication technologies**
   - ❑ **etc**

4. **Purpose of chemistry?**

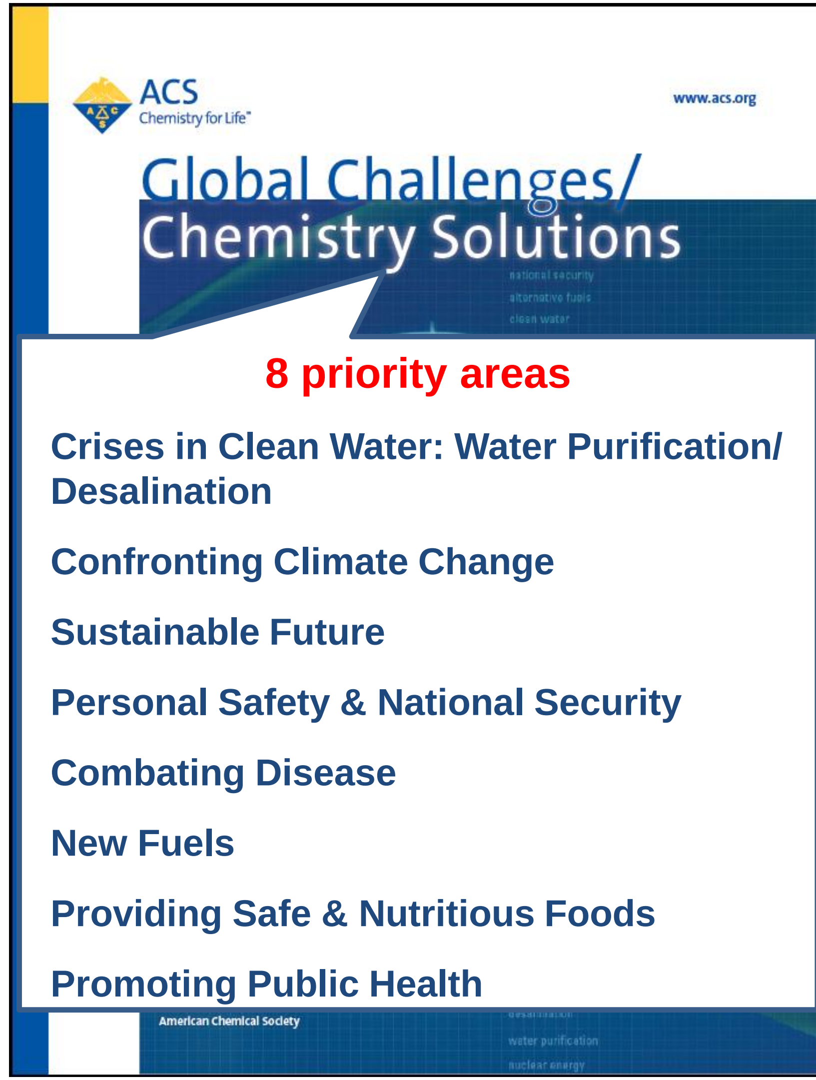
- **1 – 3 AND**
- **A science for the benefit of society**
  - **Helping to meet oncoming global challenges**

The chemical sciences have been central to global progress and will be essential to meeting oncoming global challenges – especially sustainable development

Copenhagen Consensus III, 2012
10 of the world's biggest challenges

- armed conflict
- biodiversity
- chronic diseases
- climate change
- education
- hunger and malnutrition
- infectious diseases
- natural disasters
- population growth
- water and sanitation

www.copenhagenconsensus.com/copenhagen-consensus-iii/research
How to Spend $75 Billion to Make the World a Better Place



8 priority areas

Crises in Clean Water: Water Purification/ Desalination

Confronting Climate Change

Sustainable Future

Personal Safety & National Security

Combating Disease

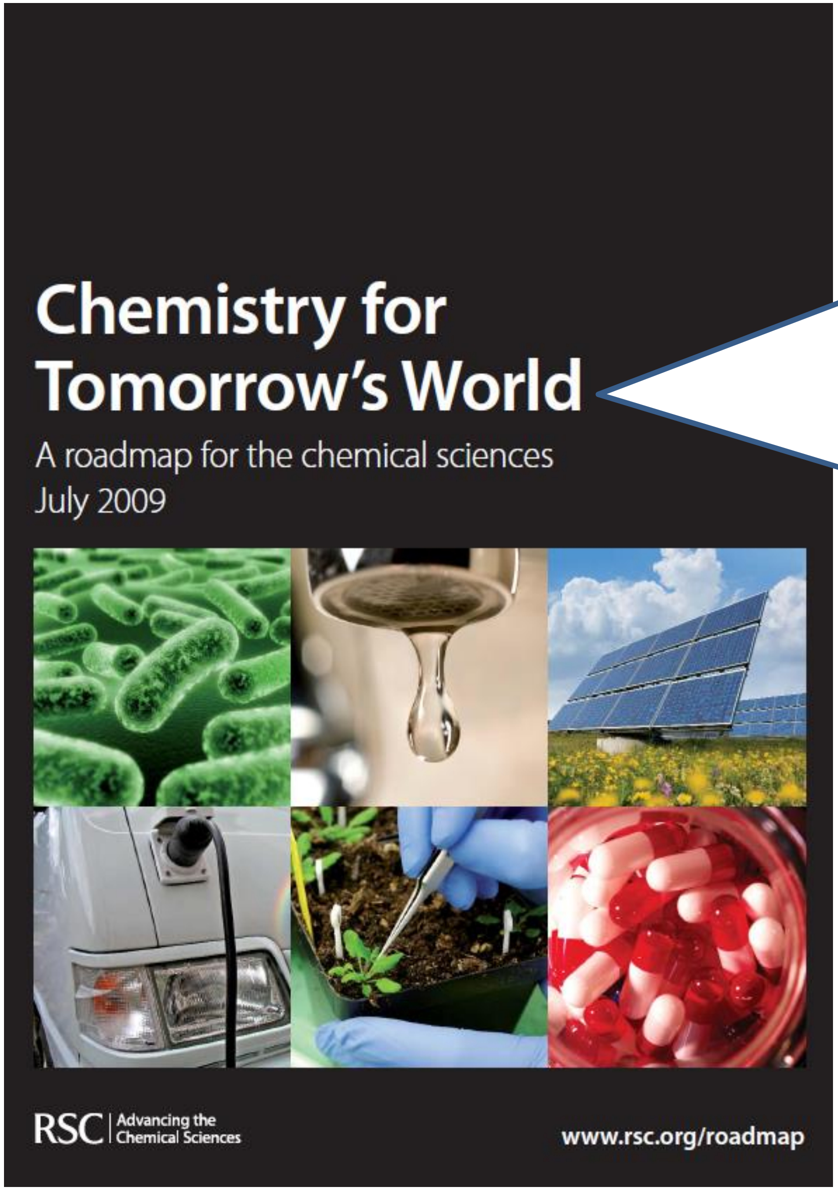
New Fuels

Providing Safe & Nutritious Foods

Promoting Public Health

www.acs.org/content/acs/en/pressroom/podcasts/globalchallenges.html

The chemical sciences have been central to global progress and will be essential to meeting oncoming global challenges – especially sustainable development



7 priority areas where chemistry can contribute

Energy: sustainability + efficiency

Food: safe, environmentally friendly, affordable

Future cities: meeting emerging needs of citizens

Human health: improving, maintaining; disease prevention

Lifestyle and recreation: sustainable route to richer, more varied lives

Raw materials and feedstocks: sustainability, preserving resources

Water and air: sustainable management of quality; availability of water resources

The chemical sciences have been central to global progress and will be essential to meeting oncoming global challenges – especially sustainable development

nature Vol 461|24 September 2009

FEATURE

A safe operating space for humanity

Identifying and quantifying planetary boundaries that must not be transgressed could help prevent human activities from causing unacceptable environmental change, argue **Johan Rockström** and colleagues.

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years[1–3]. T
geologists
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SCIENCE sciencemag.org 13 FEBRUARY 2015 • VOL 347 ISSUE 6223 1259855-1

RESEARCH ARTICLE

SUSTAINABILITY

Planetary boundaries: Guiding human development on a changing planet

Will Steffen,[1,2]* Katherine Richardson,[3] Johan Rockström,[1] Sarah E. Cornell,[1] Ingo Fetzer,[1] Elena M. Bennett,[4] Reinette Biggs,[1,5] Stephen R. Carpenter,[6] Wim de Vries,[7,8] Cynthia A. de Wit,[9] Carl Folke,[1,10] Dieter Gerten,[11] Jens Heinke,[11,12,13] Georgina M. Mace,[14] Linn M. Persson,[15] Veerabhadran Ramanathan,[16,17] Belinda Reyers,[1,18] Sverker Sörlin[19]

The planetary boundaries framework defines a safe operating space for humanity based

risk that anthropogenic activities could inadvertently drive the Earth system to a much less hospitable state.

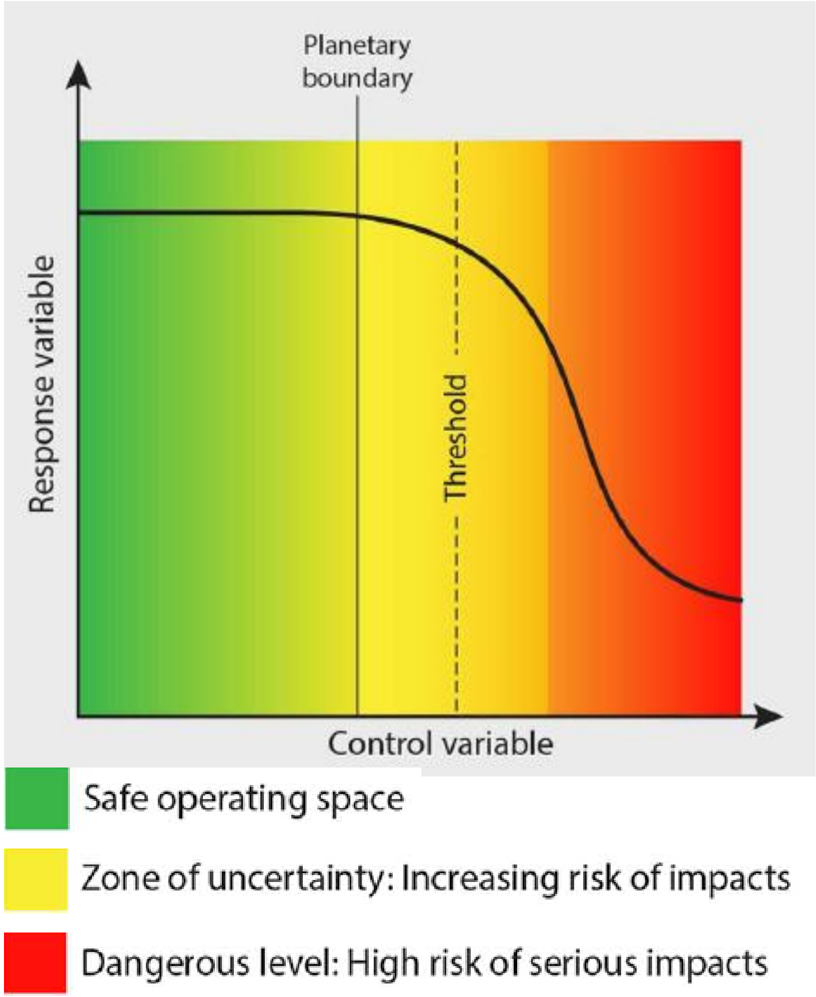
Nine processes, each of which is clearly being modified by human actions, were originally suggested to form the basis of the PB framework (*1*). Although these processes are fundamental to Earth-system functioning, there are many other ways that Earth-system functioning could be described, including potentially valuable metrics for quantifying the human imprint on it. These alternative approaches [e.g., (*4*)] often represent ways to explore and quantify interactions among the boundaries. They can provide a valuable complement to the original approach (*1*) and further enrich the broader PB concept as it continues to evolve.

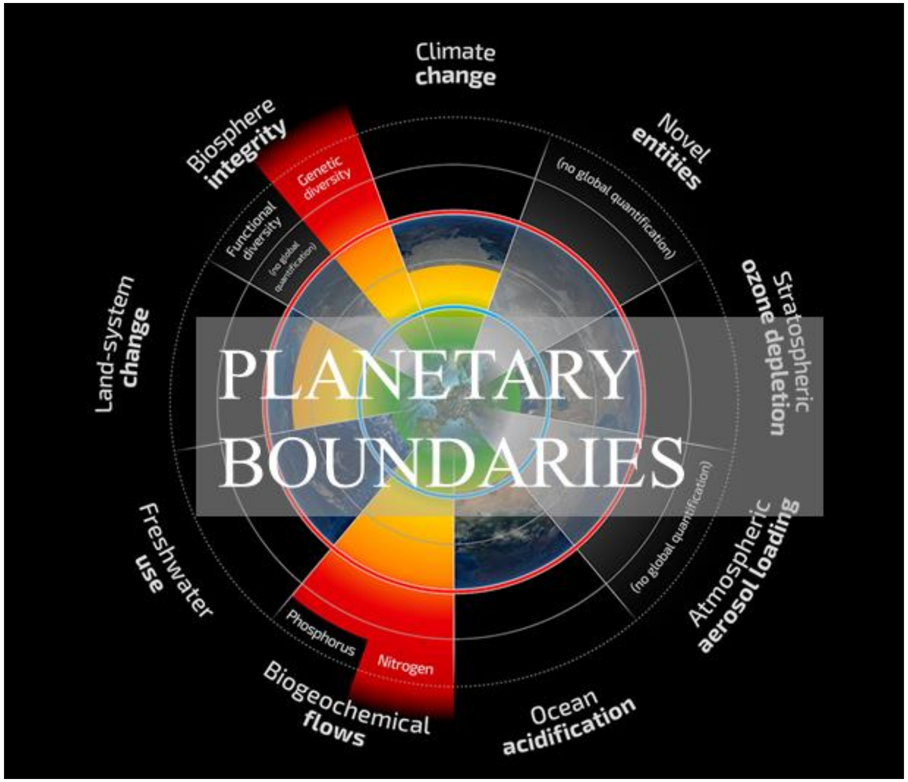
The planetary boundary framework: Thresholds, feedbacks, resilience, uncertainties

The chemical sciences have been central to global progress and will be essential to meeting oncoming global challenges – especially sustainable development

Planetary boundaries

- Human actions since the Industrial Revolution have become the main driver of global environmental change: Holocene => Anthropocene
- 9 critical areas where, once certain thresholds/tipping points are passed, there is a risk of "irreversible and abrupt environmental change"
- Planetary boundaries define a "safe operating space for humanity"





Johan Rockström, Will Steffen, et al.
Nature 2009, 461, 472-475
Science 2015, 347, Issue 6223, 1259855

The chemical sciences have been central to global progress and will be essential to meeting oncoming global challenges – especially sustainable development

Milestones on the road to sustainable development

1972 The Limits to Growth (Club of Rome)
Concept of a 'sustainable' world in which we would not see "overshoot and collapse" of the global system as the consequence of interactions between the Earth's and human systems

1987 Brundtland Report: UN World Commission on Sustainable Development
Development that meets the needs of the present without compromising the ability of future generations to meet their own needs

1992 UN Conference on Environment and Development (Rio: 'Earth Summit')
Earth Charter (Agenda 21): building of a just, sustainable, and peaceful global society in 21st C
- ***"socially inclusive and environmentally sustainable economic growth"***

2012 United Nations Conference on Sustainable Development (Johannesburg: 'Rio+20')
"The Future We Want": 192 governments renewed their political commitment to sustainable development

2009 - 2015: Planetary boundaries
Nine boundaries identified

2015 United Nations Agenda 2030
17 Sustainable Development Goals: adopted by all 193 Member States

The chemical sciences have been central to global progress and will be essential to meeting oncoming global challenges – especially sustainable development

2015 UN Sustainable Development Goals for 2030

17 Sustainable Development Goals (SDGs)

1: No poverty
2: Zero hunger
3: Good health and well-being
4: Quality education
5: Gender equality
6: Clean water and sanitation
7: Affordable and clean energy
8: Decent work and economic growth
9: Industry, innovation and infrastructure
10: Reduced inequalities
11: Sustainable cities and communities
12: Responsible consumption and production
13: Climate action
14: Life below water
15: Life on land
16: Peace, justice and strong institutions
17: Partnerships for the Goals

Shared global responsibility
"…leaving no-one behind"

https://sustainabledevelopment.un.org

The chemical sciences have been central to global progress and will be essential to meeting oncoming global challenges – especially sustainable development

Crises facing the planet in the 21st century

- **Planetary systems**
  - Climate change
  - Atmospheric pollution
  - Ocean contamination
  - etc
- **Health**
  - Population, urbanization, ageing
  - Emerging and re-emerging diseases
  - Traditional model of drug development fails in some important areas
- More people – but resource constraints
  - Food
  - Water
  - Energy
  - Materials
  - Environment (air, land, sea)

⇔

- It's a dirty world
  - Pollution of land, sea, air harms the entire ecosphere
- It's a fake world
  - Counterfeiting and adulteration affect food, medicine, environment

The chemical sciences can contribute to solutions.
Challenges in:
- Science content
- Capacity for science
- Governance of science

The chemical sciences have been central to global progress and will be essential to meeting oncoming global challenges – especially sustainable development

commentary

The role of chemistry in inventing a sustainable future

Stephen A. Matlin, Goverdhan Mehta, Henning Hopf and Alain Krief

The Sustainable Development Goals adopted at a UN summit in September 2015 address many of the great challenges that our planet faces this century. Chemistry can make pivotal contributions to help realize these ambitious goals, but first it must undergo major changes in its priorities, approaches and practices.

One of the most important and

as many major practical advances seen in

inte

Chemistry can make pivotal contributions to help realize these ambitious goals, but first it must undergo major changes in its priorities, approaches and practices.

spelled out in 17 Sustainable Development Goals (SDGs) with a target date of 2030 (Box 1); progress towards them will be measured against 169 specific indicators[2]. These SDGs represent a profound shift in the world's approach to development over the past 15 years. Whereas the Millennium Development Goals agreed by governments at the UN in 2000 focused on specific problems of the world's poor and shaped the development aid policies of the richest countries[3], the new SDGs

chemistry and related molecular sciences. The chemical sciences can — and must — play a key role in developing the processes, products and monitoring mechanisms that the SDGs envisage. These emerging approaches must involve innovation that is frugal[6], disruptive[7] and widely applicable as well as sustainable. But to do so, all domains of chemistry — academia, industry, funding agencies, the professional bodies and associations at national and

a host of materials including polymers, plastics, semiconductors and solid-state display devices; agents for crop protection and plant growth; pharmaceuticals and much else — have been a major factor in the advances in human wealth, health and well-being over the past two centuries[8] and justify chemistry's claim[9] to be the 'quality-of-life' science *par excellence*. It promises to go on being the source of innovative new products and processes, including smart

Matlin et al, Nature Chemistry 2015, 7, 941-3

The chemical sciences have been central to global progress and will be essential to meeting oncoming global challenges – especially sustainable development

commentary

One-world chemistry and systems thinking

Stephen A. Matlin, Goverdhan Mehta, Henning Hopf and Alain Krief

The practice and overarching mission of chemistry need a major overhaul in order to be fit for purpose in the twenty-first century and beyond. The concept of 'one-world' chemistry takes a systems approach that brings together many factors, including ethics and sustainability, that are critical to the future role of chemistry.

Chemistry has achieved outstanding success over the past two centuries in terms of advancing fundamental knowledge as well as its impact on applications relating to human health, wealth and well-being[1]. However, a number of observations suggest that chemistry is facing an existential crisis of sorts, including reflections from the fields of education[2], industry[3], the environment[4] and the public arena[5]. If this is the case, there are a number of likely contributory factors, including (1) the discipline has not been effective in reinventing itself or projecting its contemporary advances on prominent external platforms, (2) it is intrinsically

© FRAZER HUDSON / ALAMY STOCK PHOTO

as an exciting scientific pursuit generating groundbreaking new discoveries in its own right is giving way to its portrayal as a 'service science' for other fields.

Attitudes of the general public, media and policy-makers towards chemistry and its practitioners are complex. They sometimes recognize chemistry's pivotal utilitarian role that impinges on every facet of life[9] while at other times they focus on negative aspects, such as its ability to cause harm to people and the environment through deliberate (for example, chemical warfare) or accidental or unintended (chemical spillages, disasters in chemical plants, toxic side effects of drugs and food additives,

Matlin et al, Nature Chemistry 2016, 8, 393-8

Chemistry in the 21st century

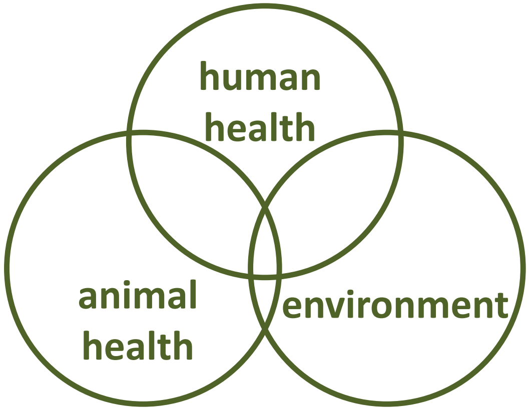
'One-world chemistry'

Aims to be:

- A science for the benefit of society
  - Ethical practice
  - Systems thinking
  - Cross-disciplinarity

Recognises:

- Earth is a single system in which the health of human beings, animals and the environment are all strongly interconnected: all three must be taken into account in considering the impacts of chemistry

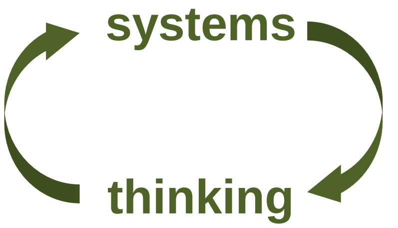


Implications for chemistry – including for chemistry education

- Idea of chemistry
- Chemistry in the context of its applications
- Chemistry in the context of its impacts
  - Thinking about systems and how they function and interact
  - Connecting science principles with sustainability goals
  - Using cross-disciplinary approaches

Matlin et al, Nature Chemistry 2016, 8, 393-8

Implications for chemistry education



System

- an interconnected set of elements that is coherently organized in a way to achieve a function or purpose.

Systems thinking

- Using strategies to develop understanding of the interdependent components within and among complex, dynamic systems
- Seeing and understanding systems as wholes rather than as collections of parts – as a web of interconnections that creates emerging patterns which help to identify the leverage points that lead to desired outcomes

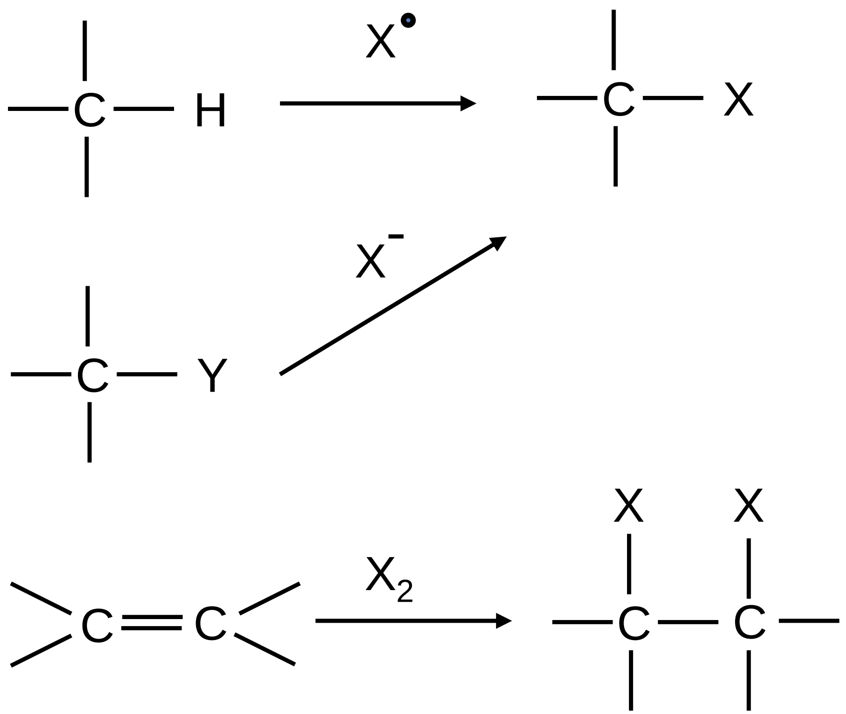
adapted from http://watersfoundation.org

Implications for chemistry education

Planetary boundaries: Stratospheric ozone depletion

Synthesis of alkyl halides

X_2	m.pt.	b.pt.
F_2	-220	-188
Cl_2	-101	-35
Br_2	-7	59
I_2	114	184



CH_3-X	b.pt.
F	-78.4
Cl	-23.8
Br	3.5
I	42.4

<u>Examples of applications</u>

Polyvinyl chloride - PVC

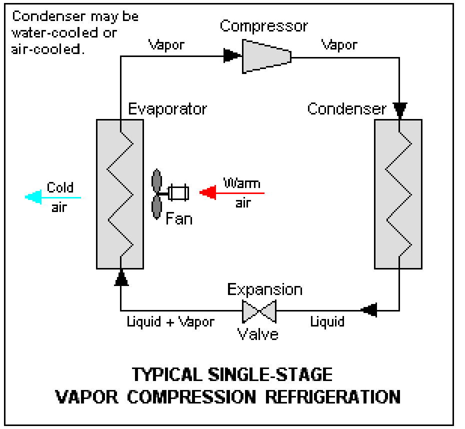
Polychlorinated biphenyls – PCBs

Dichlorodiphenyltrichloroethane – DDT

Fluorocarbons

- **Anaesthetics – Fluothane**
- **Polytetrafluroethylene – PTFE**
- **Refrigerants**

Fluorocarbons



Refrigerants

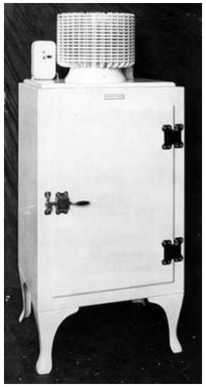
A compressed gas gets colder when it expands; a liquid gets colder when it evaporates

- **Ideal materials have b.pt. < room temp: e.g. NH_3 (-27ºC) [X corrosive, toxic]**

1928 **Thomas Midgley (General Motors) improved synthesis of chlorofluorocarbons (CFCs), e.g. CF_2Cl_2 (b.pt. -30ºC).**

$$CCl_4 + HF \xrightarrow{SbF_3Cl_2} CFCl_3 + CF_2Cl_2 + HCl$$

Patented and developed as Freon®; used in fridges from 1930; by 1960s 'halons' also widely used in aerosol cans and in fire-fighting



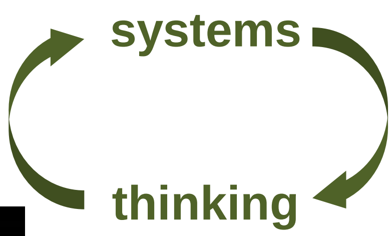
General Motors *Monitor Top* SO_2 fridge 1927

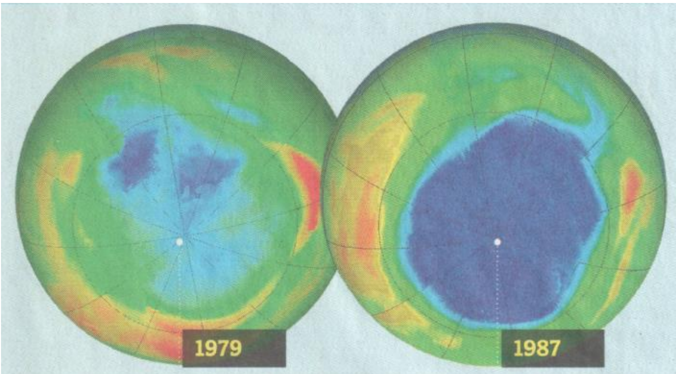
1957 **Electron capture detector invented by James Lovelock**

- **Extremely sensitive for detection of halogenated compounds in gas chromatography. Late 1960s, Lovelock first to detect the widespread presence of CFCs in the atmosphere**

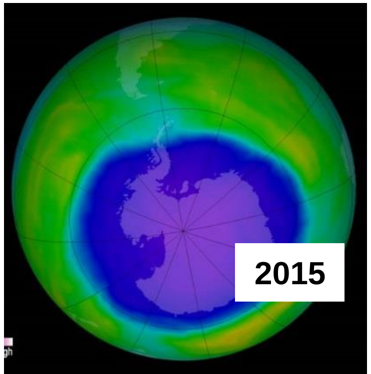
1974 **Mario Molina and Sherwood Rowland (Nobel 1995): photolysis of atmospheric CFCs releases chlorine atoms which break down ozone.**

- **Since 1970s: 4 %/decade decline in atmospheric O_3 and much larger annual springtime decrease in stratospheric O_3 over S. polar region ('ozone hole' reported in *Nature*, 1985)**



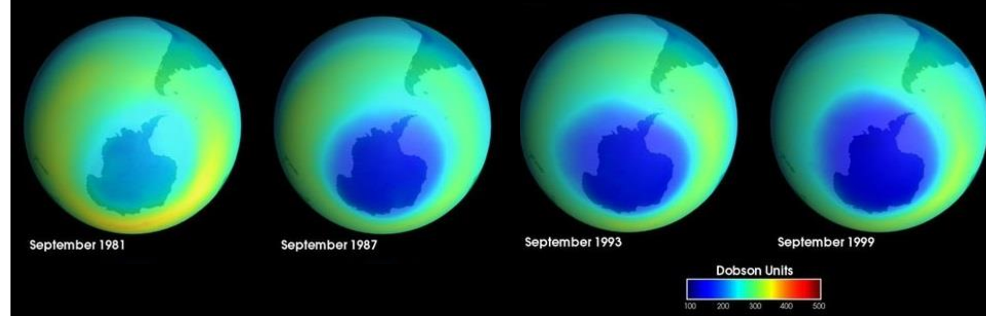


Two of the images that raised global alarm over the hole in the ozone layer (NASA-Corbis)



4th largest Antarctic ozone hole recorded 2 October 2015 over the southern pole (NASA)

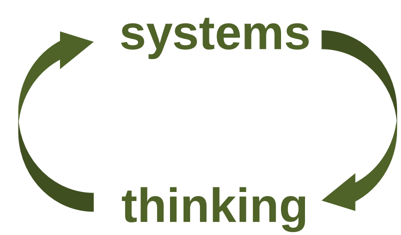
Antarctic ozone hole 1981-1999
Images from the Total Ozone Mapping Spectrometer (TOMS)



1977 United Nations Environment Programme (UNEP): **World Plan of Action on the Ozone Layer** (research and monitoring of ozone layer)
1981 work began to draft a global framework convention on stratospheric ozone protection.
1985 **Vienna Convention**: States agree to cooperate in relevant research and scientific assessments of the ozone problem, exchange information, and adopt "appropriate measures" to prevent activities that harm the ozone layer. Obligations are general: no specific limits on chemicals that deplete the ozone layer.

1987 **Montreal Protocol** on Substances that Deplete the Ozone Layer signed; came into force 1 January 1989

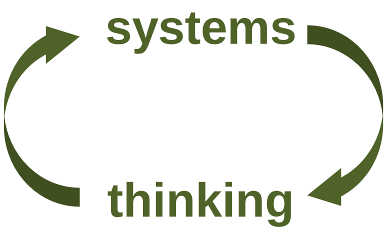
- Rapid phasing out CFCs
- Slower phasing out of hydrochlorofluorocarbons (HCFCs), 1996-2030



"To understand what was happening to the ozone layer, researchers… had to **bridge traditional scientific disciplines** and **examine the earth as an interrelated system of physical, chemical, and biological processes** occurring on land, in oceans, and in the atmosphere – processes that were themselves **influenced by economic, political, and social forces**."

RE Benedick (US State Department, Chief US Negotiator on the Montreal Protocol). www.eoearth.org/view/article/155895/

Implications for chemistry education



Strategies & tools to assist systems thinking in chemistry education

- **Learning from rich contexts**
  http://pubs.acs.org/doi/abs/10.1021/sc500415k

- **Case-based learning**

- **Problem-based learning**

- **Next Generation Science Standards –3D learning**
  www.nextgenscience.org

- **Cross-cutting and cross-disciplinary concepts***
  Bringing together knowledge, methods, tools from different disciplines

- **Chemical thinking learning progressions**
  Describes likely pathways in the evolution of students' chemical thinking with training in the discipline
  Sevian & Talanquer CERP 2014, 15, 10-23

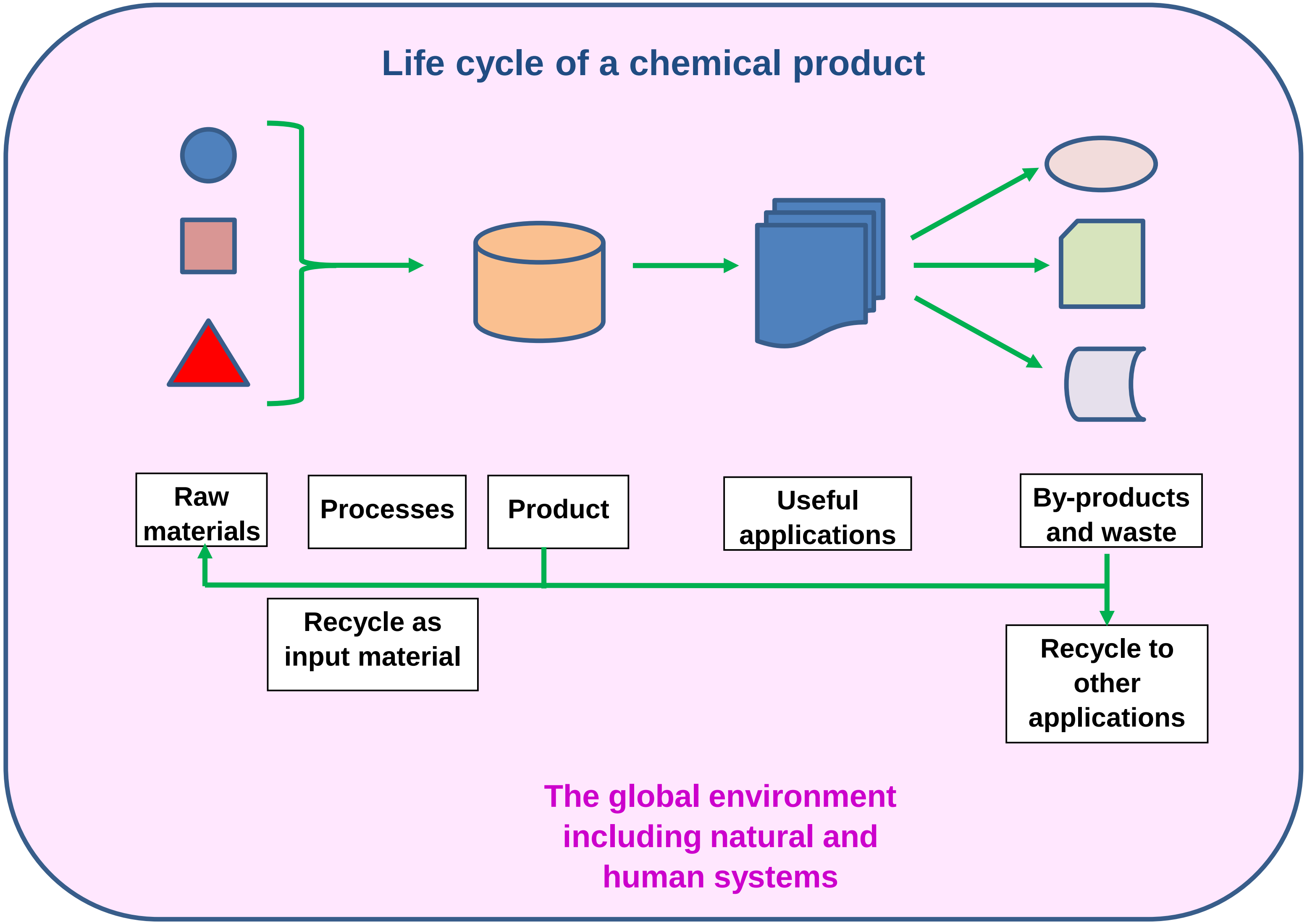
- **Life cycle analysis***
  Understanding product life cycle concepts has fundamental value to students

(Hislop-Hook, Ooms, Mahaffy, 2018 in preparation)

Implications for chemistry education

systems thinking

Life cycle analysis



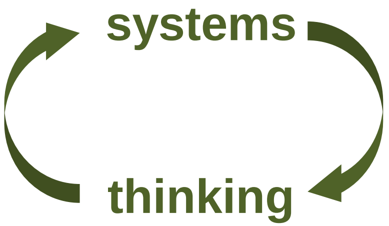
Implications for chemistry education

systems thinking

Green Chemistry

Invention, design and application of chemical products and processes to reduce or to eliminate the use and generation of hazardous substances, and where possible utilize renewable raw materials

Paul Anastas and John Warner. Green Chemistry: Theory and Practice. New York, Oxford University Press: 1998



Implications for chemistry education

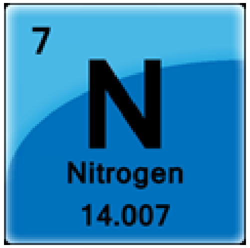
Molecular basis of sustainability

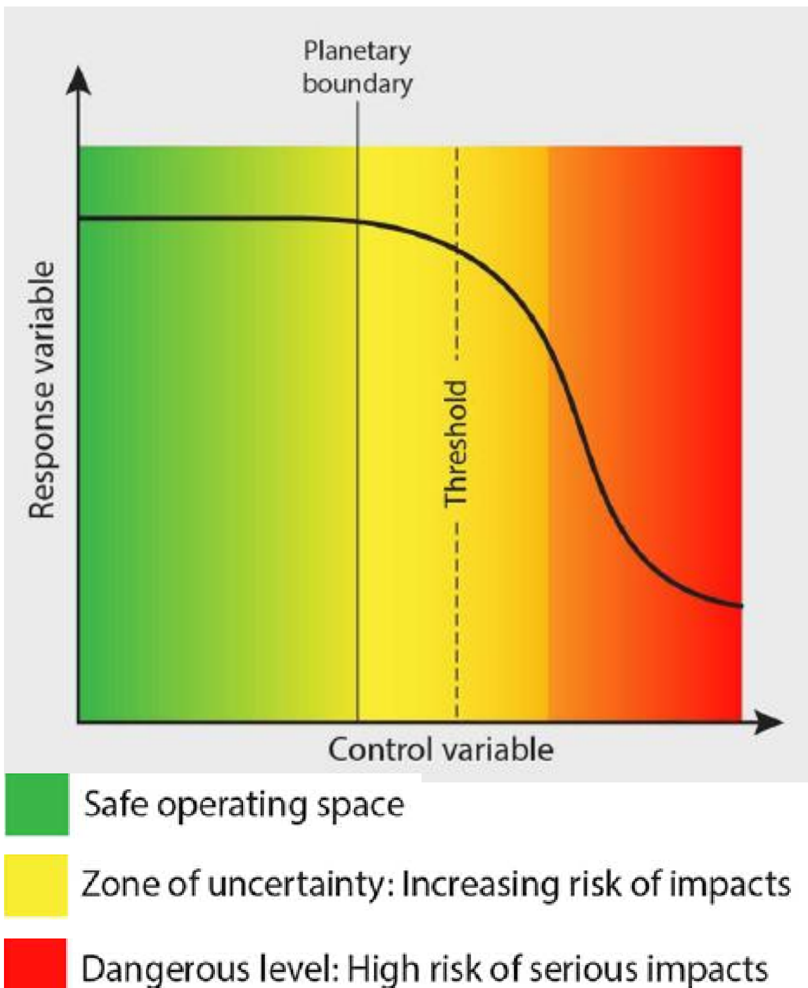
The <u>design</u> and application of chemical products and processes that reduce or eliminate the use and generation of hazardous substances

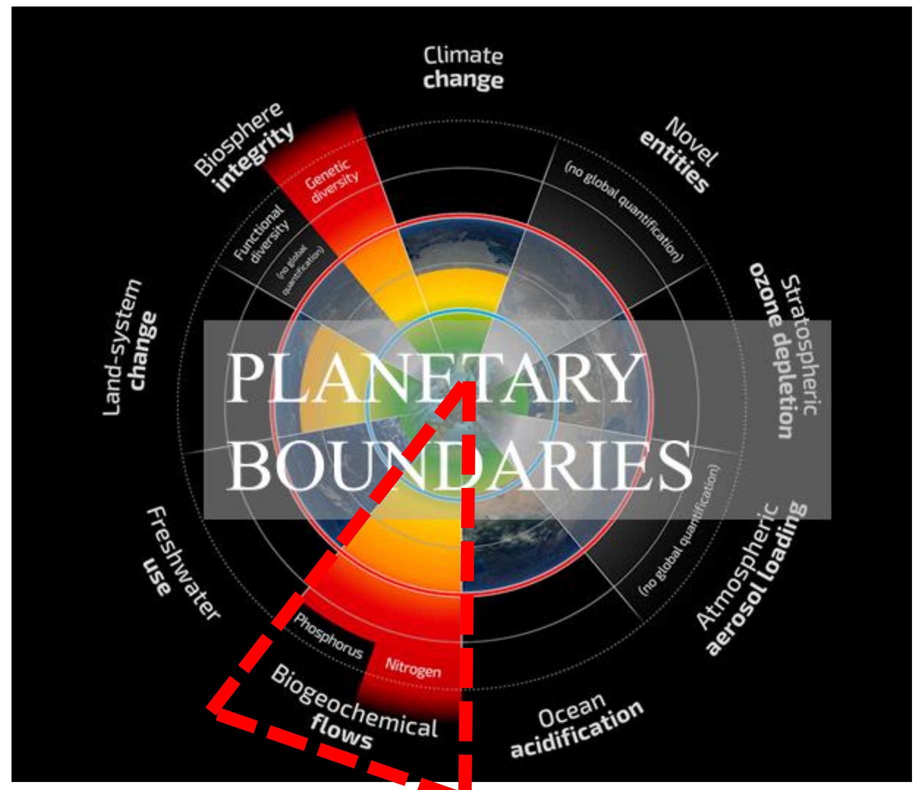
- Defining green chemistry through design declared a paradigm shift from when chemists could plead ignorance of or ambivalence to the consequences of their science
- Chemists are the ones who possess the ultimate responsibility of putting forethought and consideration of those consequences into the design.
- Consider the implications of the chemical bond. Example questions:
  - What are the consequences of the C-H bond on our current energy system?
  - What are the consequences of the C-F bond on stratospheric ozone?
  - What are the consequences of the C≡C bond on toxicity?
  - What are the consequences of the O=C=O stretching energy on global climate change?

"By understanding that many of our environmental concerns are derived from molecular characteristics, we as chemists can realize that many of the solutions are, potentially, also molecular."

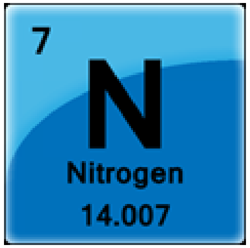
Paul Anastas, Julie B. Zimmerman. The Molecular Basis of Sustainability. Cell Press: Chem 2016, 1, 10-12.

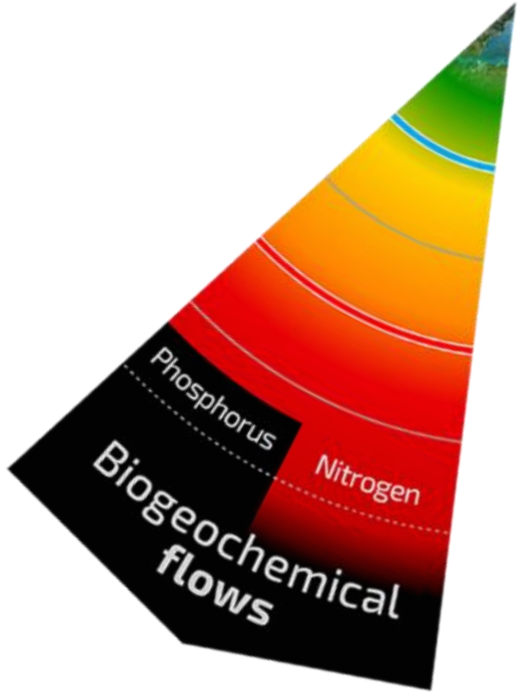




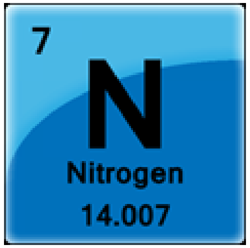


Johan Rockström, Will Steffen, et al.
Nature 2009, 461, 472-475
Science 2015, 347, Issue 6223, 1259855



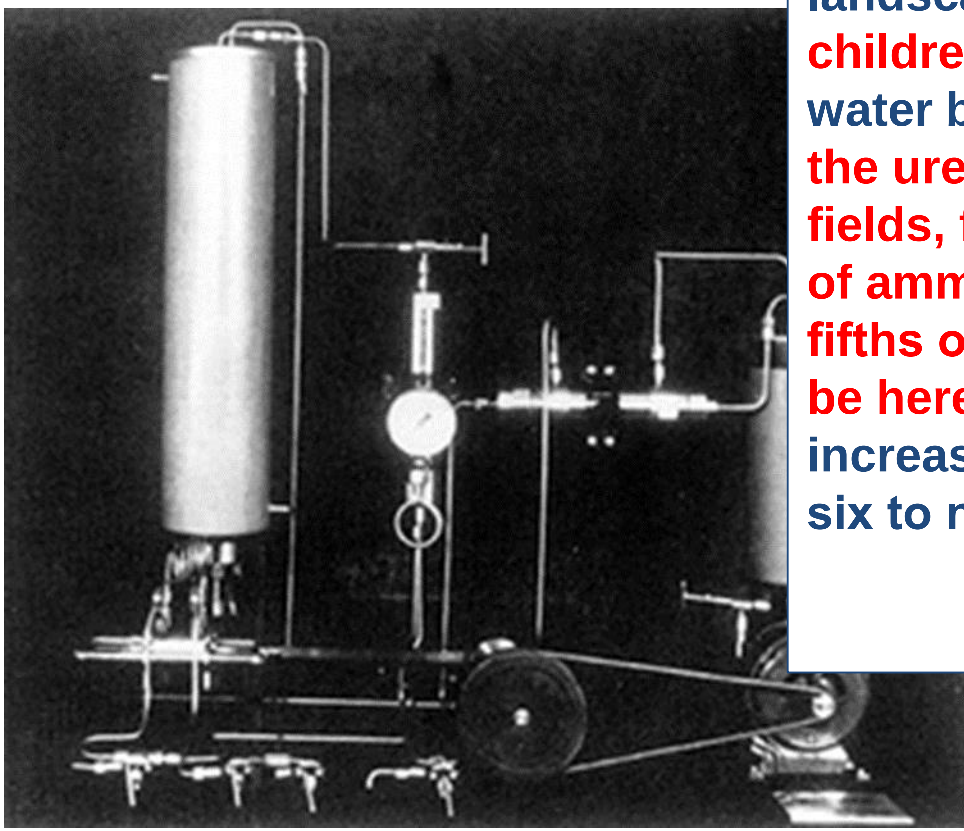


Control variable(s)	Planetary boundary (zone of uncertainty)	Current value of control variable
N Global: Industrial and intentional biological fixation of N	62 Tg N yr^{-1} (62–82 Tg N yr^{-1}). Boundary acts as a global 'valve' limiting introduction of new reactive N to Earth System, but regional distribution of fertilizer N is critical for impacts.	~150 Tg N yr^{-1}



The most important technological invention of the 20th Century?

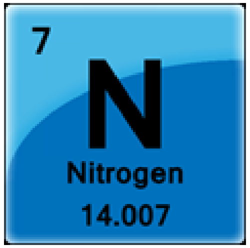
Haber-Bosch Process



"When you travel in Hunan or Jiangsu, through the Nile Delta or the manicured landscapes of Java, remember that the children running around or leading docile water buffalo got their body proteins via the urea their parents spread on the fields, from the Haber–Bosch synthesis of ammonia. Without this, almost two-fifths of the world's population would not be here - and our dependence will only increase as the global count moves from six to nine or ten billion people."

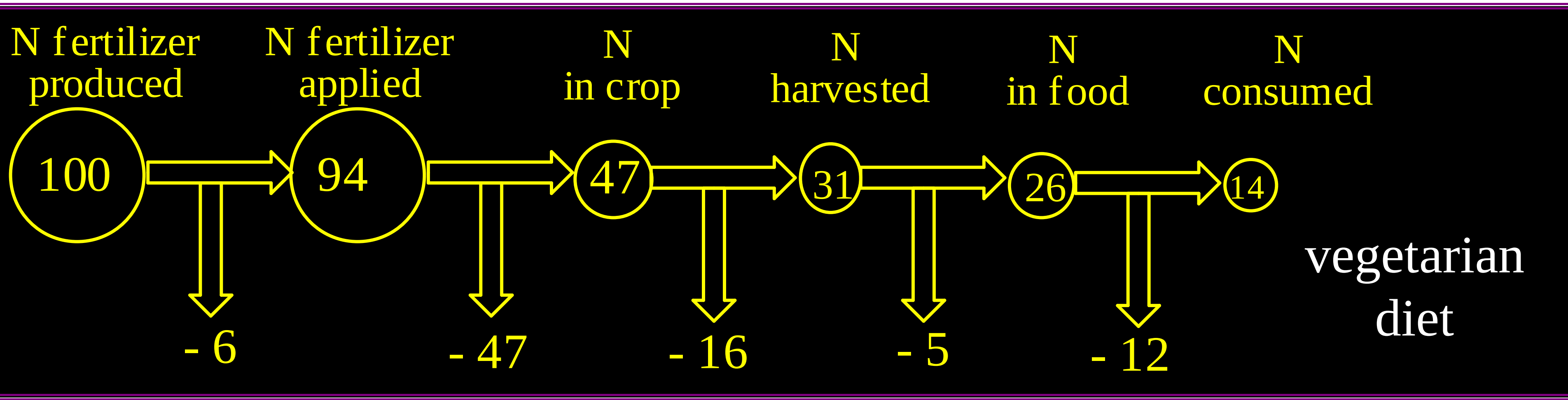
V Smil, Nature 1999, 400, 415

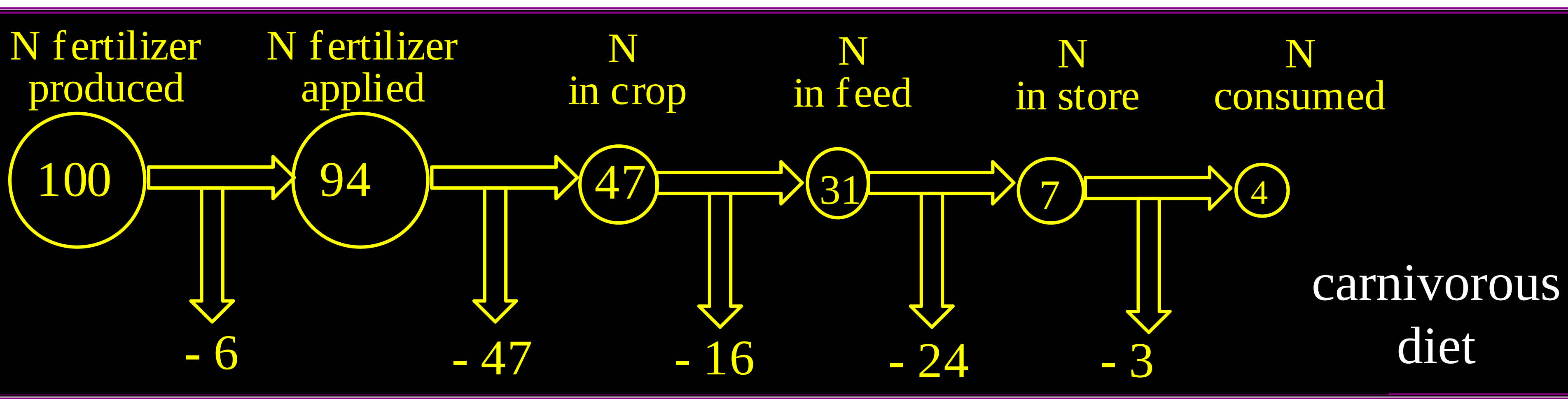
$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$$



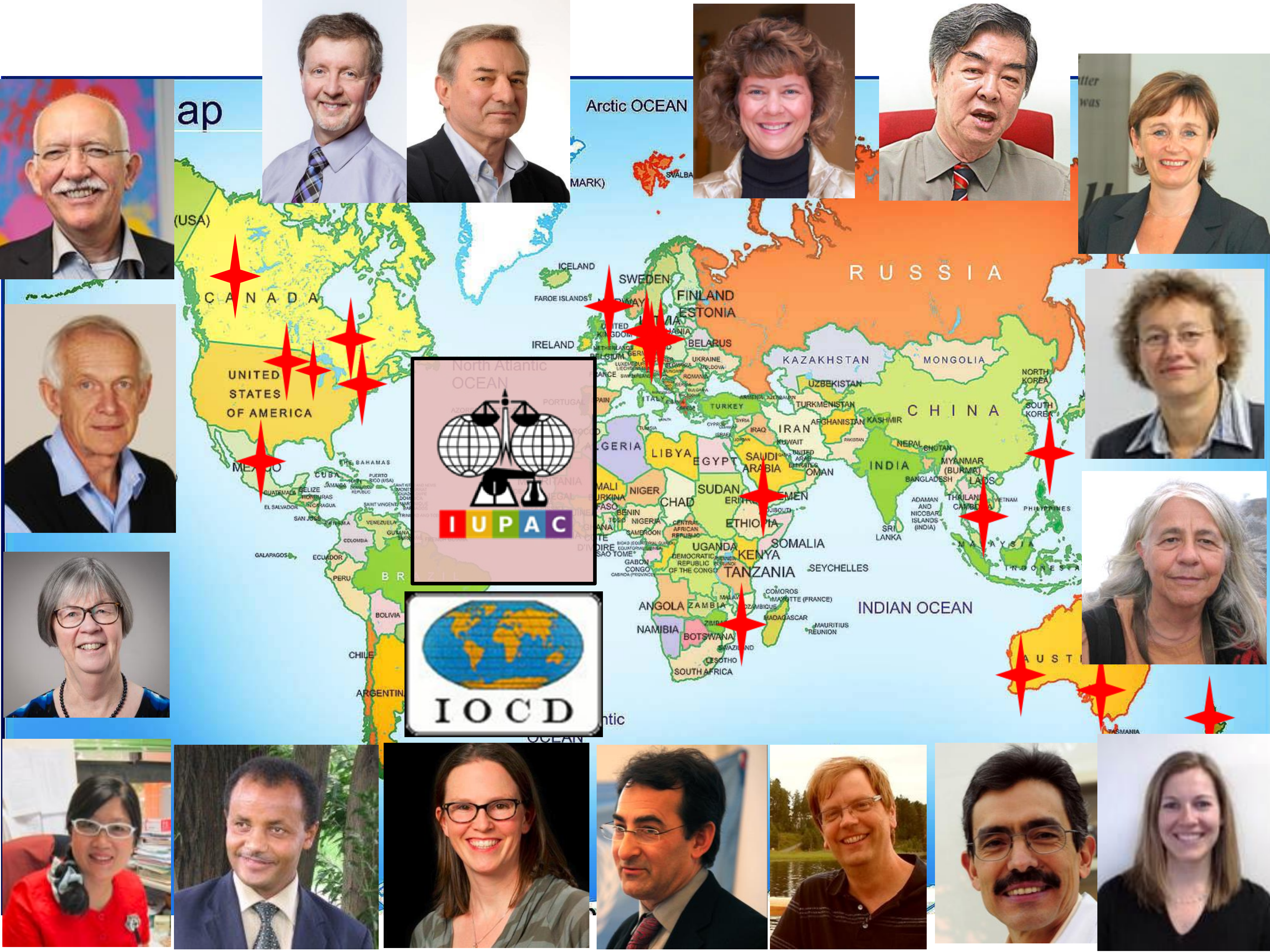
The most important technological invention of the 20th Century?

… but a failure of systems thinking?





Mahaffy, Bucat, Tasker, et. al, *Chemistry: Human Activity, Chemical Reactivity*, Nelson/Cengage, 2015, adapted from J. N. Galloway & E. B. Cowling, 31, Ambio, March 2002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TURKMENISTAN
TURKEY
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CHINA
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