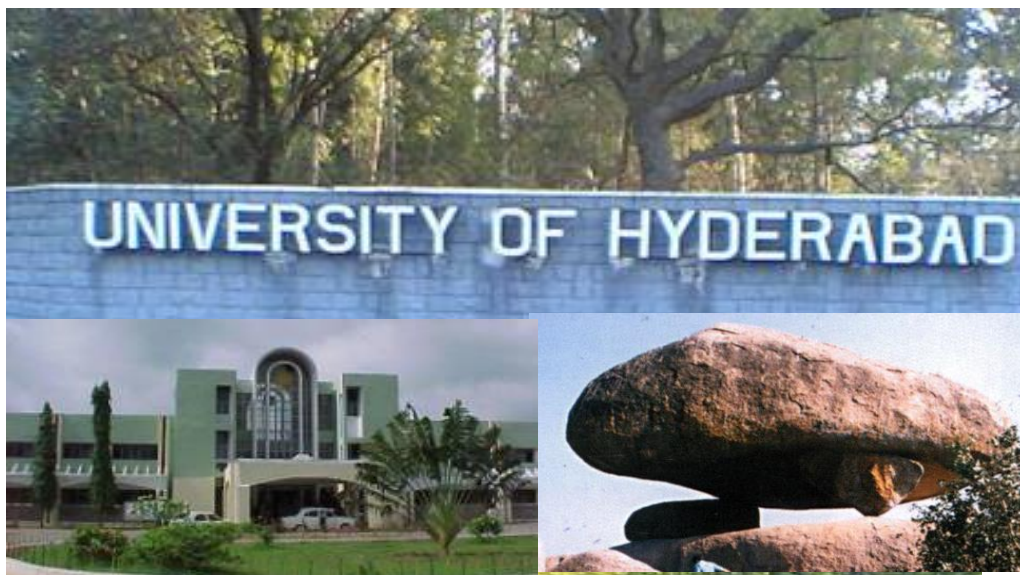
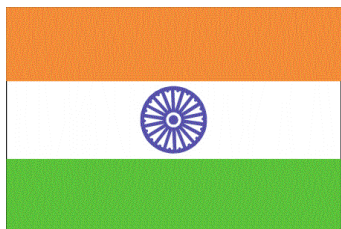


Goverdhan Mehta

Chemistry - A 21st Century Science for Global Sustainability: Is it future ready?



A 'selfie' with the chemical world.....



**Introducing Chemistry through the Lens of Earth's Systems:
What Role Can Systems Thinking Play in Developing
Chemically and Environmentally Literate Citizens?**

J. Kornfeld, S. Stokoe. *J. Chemical Education* **2019**, 96, 2910-2917

A bouquet of 'matters' that matter

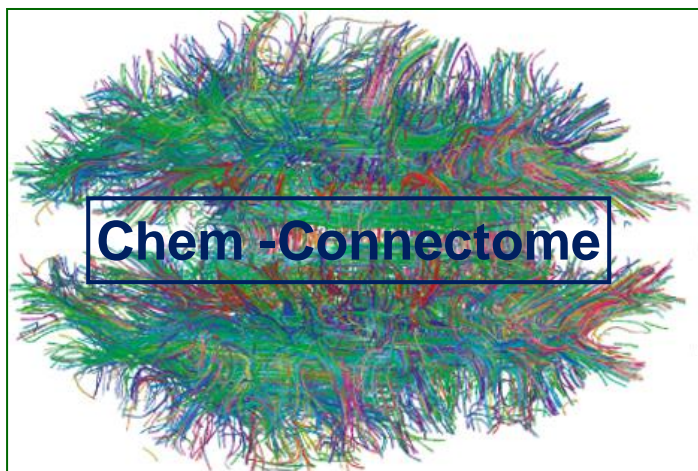


Un mélange de beaucoup de choses

"Chemistry ought not to be for chemists alone"

- Miguel de Unamuno

'...Life, Universe and Everything'



Chemistry – a source of happiness....

'...I feel sorry for people who don't know anything about chemistry. They are missing an important source of happiness....' - Linus Pauling



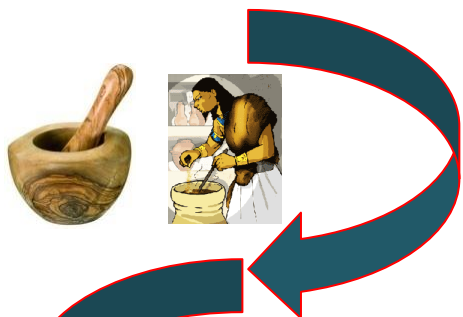
1901-1994

Chemistry is in everything and everything is in it,
it is the basis of life, without it we wouldn't exist.

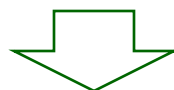
Chemistry is ubiquitous/omnipresent

Chemistry – Tracing the roots and to the present

BCE

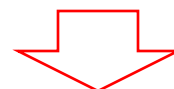
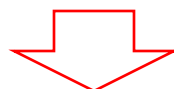


Art & craft of mixing substances



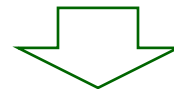
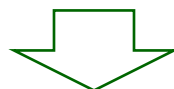
A giant knowledge leap

Alchemy to modern science



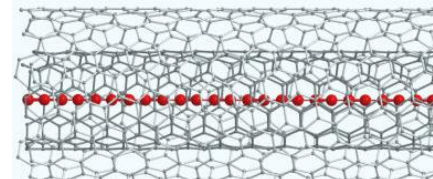
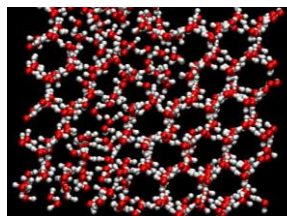
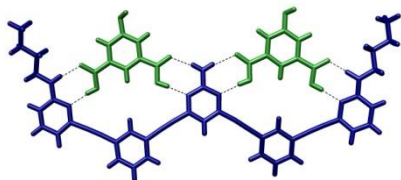
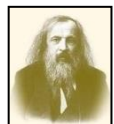
Evidence based science

Discipline in a Table - systematization



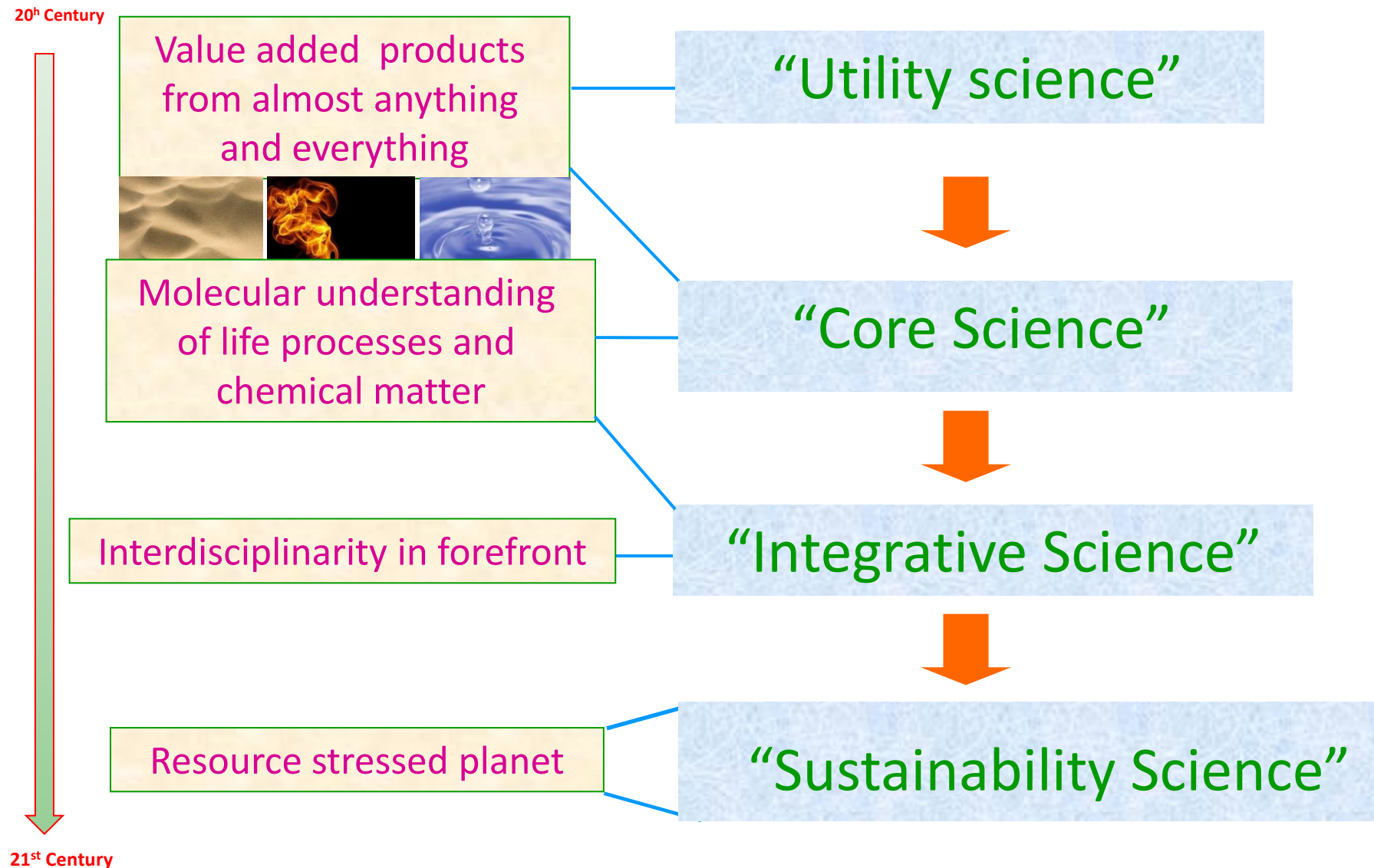
Mendeleev's Periodic Law

'Molecularization' of chemical matter

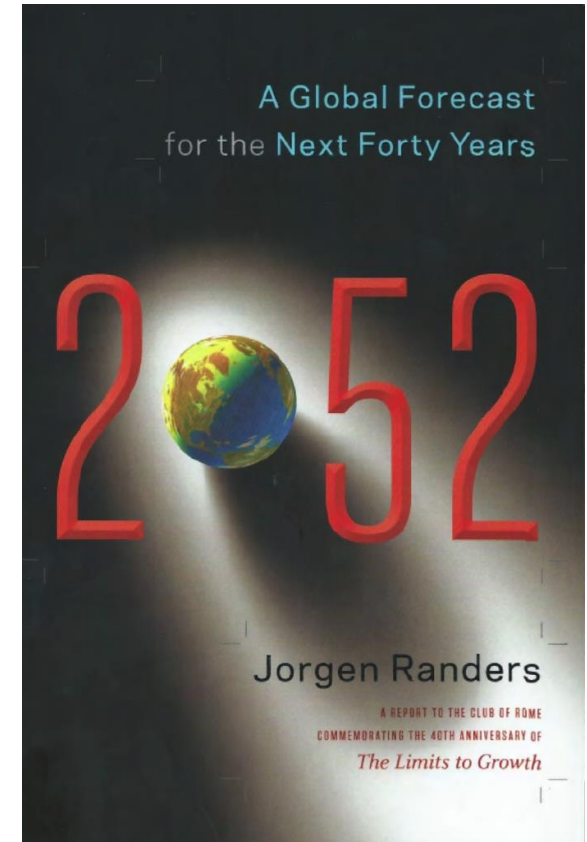
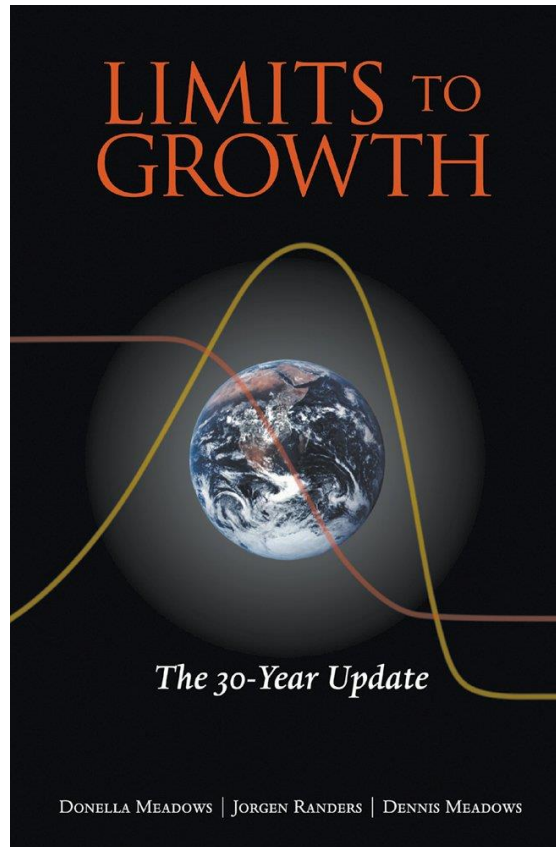
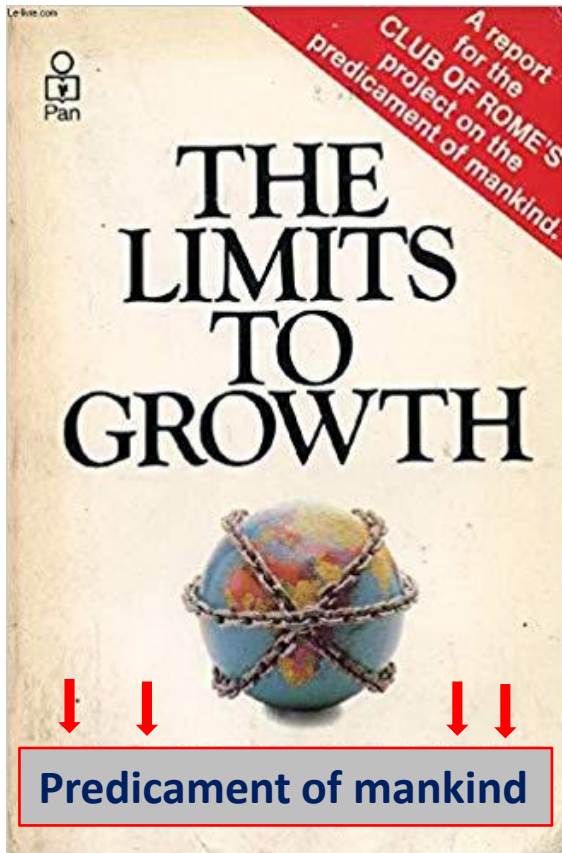
A color-coded version of Mendeleev's periodic table of elements.

20th Century

A century of evolutionary march of chemistry



A 'foresight' analysis of our world (1972- 2052)

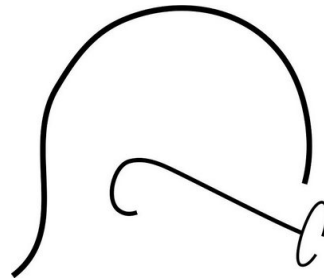


- Gain insights into the limits of our world system and the constraints it puts on human numbers and activity.
- Identify and study the dominant elements, and their interactions, that influence the long-term behavior of world systems.

A Foresight analysis of our world (1972- 2052)

Understanding of planetary boundaries....

Late lessons from early warnings – decades lost!



“.....The world has enough for everyone's need, but not enough for everyone's greed.” - **Gandhi**

A Foresight analysis of our world (1972- 2052)

Understanding of planetary boundaries....

Late lessons from early warnings – decades lost!

Silver lining!

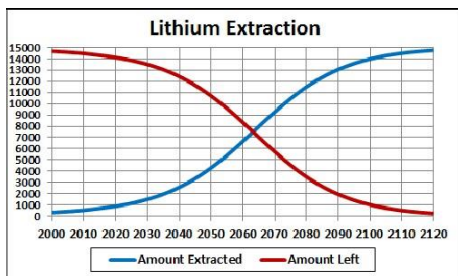
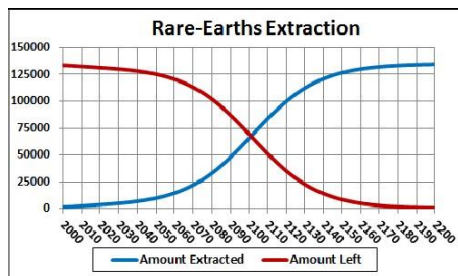
United Nations Sustainable Development Goals, 2015-30



Six of the 17 goals map into chemical sciences

New world realities – A pivotal role for chemistry

20th Century



All material used on our planet is chemically processed
>1000...BnT p.a.; producing >100...BnT of waste!
★★★ **THIS IS UNSUSTAINABLE????** ★★★

Chemistry can pave the way: greener, leaner and efficient processing, recycling.

Rapid depletion of lithium (White Gold) and rare earths

CO₂
<415 ppm

Resource stressed planet

“Sustainability Science”

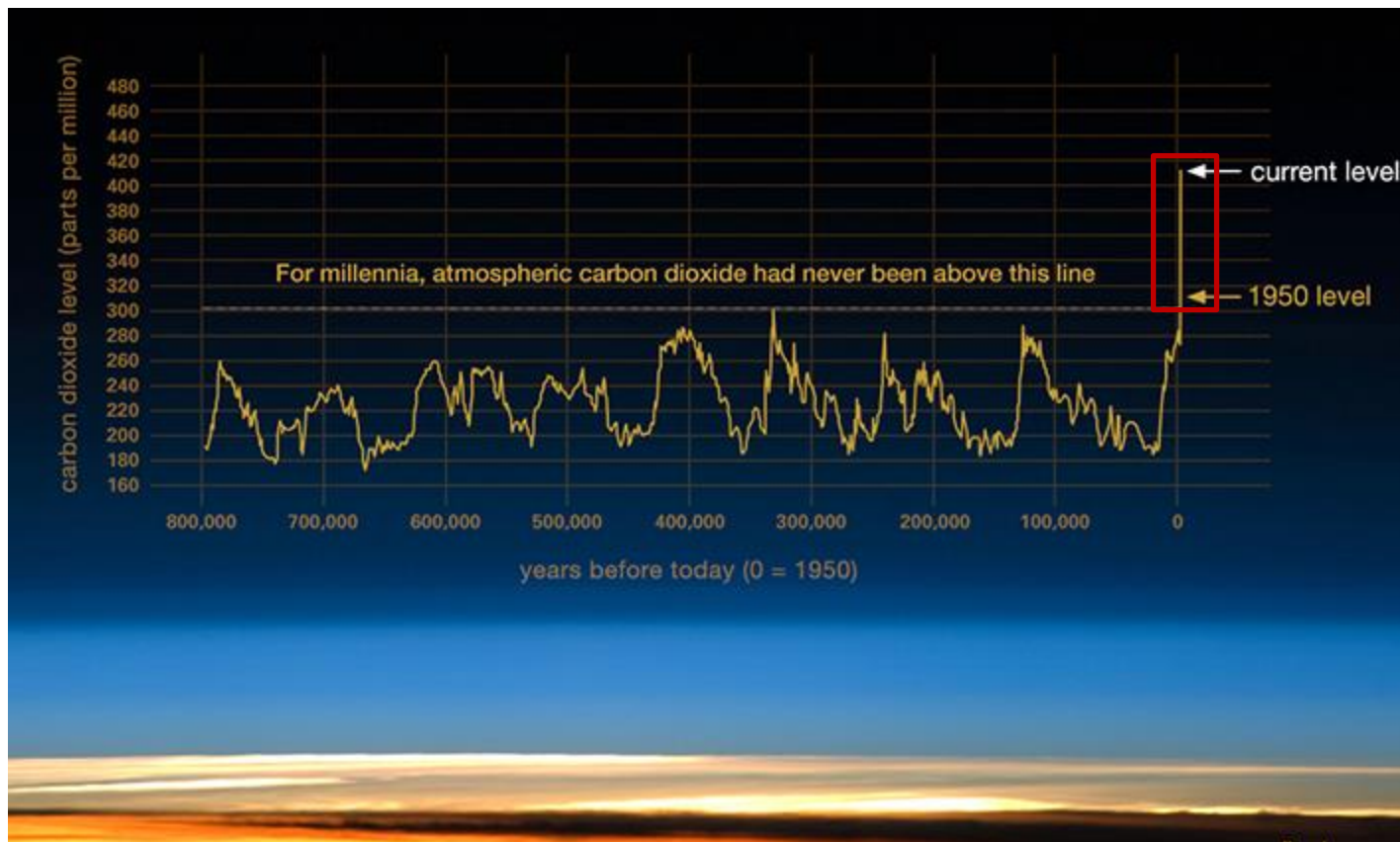
21st Century

S. A. Matlin, G. Mehta, H. Hopf, A. Krief. *Nature Chemistry* **2015**, 7(12), 941-943

H. Hopf, A. Krief, G. Mehta and S. A. Matlin, SciDev. Net. 2019 (Appeared on April 22, World Earth Day)

New world realities – A pivotal role for chemistry

20^h Century



The Mauna Loa Observatory, took a reading of 415.26ppm on 11 May – thought to be the highest since humans evolved.

21st Century

S. A. Matlin, G. Mehta, H. Hopf, A. Krief. *Nature Chemistry* **2015**, 7(12), 941-943

H. Hopf, A. Krief, G. Mehta and S. A. Matlin, SciDev. Net. 2019 (Appeared on April 22, World Earth Day)

A transformative perception of chemistry

More from less

Resource prudence

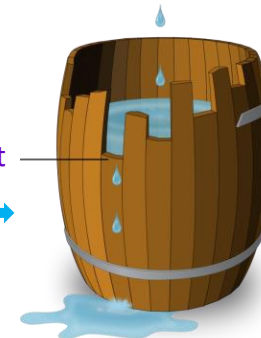


Justus von Liebig
(1803-1873)

Liebig's Law

'..Growth is controlled not by the total amount of resources available, but by the scarcest resource..'

Limit



Liebig's barrel

A world of *...now passé*

'Waste' does not exist : Chemical matter only changes 'form', so waste is actually material awaiting further use.

Circular Chemistry

A transformative perception of chemistry

More from less

Resource prudence

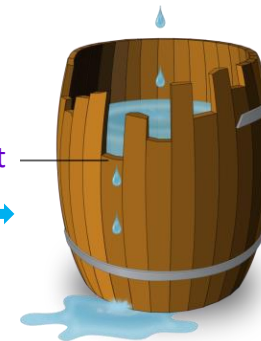


Justus von Liebig
(1803-1873)

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'..Growth is controlled not by the total amount of resources available, but by the scarcest resource..'

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Liebig's barrel

'Waste' does not exist : Chemical matter only changes 'form', so waste is actually material awaiting further use.

Circular Chemistry

Chemistry: living prophecies



Antoine Lavoisier
1743-1794



Humphry Davy
1778-1829



Jacob Berzelius
1779-1848



Michael Faraday
1791-1867



Friedrich Wohler
1800-1882



Justus von Liebig
1803-1873



Marcellin Berthelot
1827-1907



'Nothing is lost, nothing is created,
everything is transformed'

- Antoine Lavoisier

'Green' is in the DNA of Chemistry

But, there are some worrisome mutations ?

'die chemie ist also die
Lehre von den stofflichen
metamorhosen der materie'

- Kekulé



← Wohler
1827

'Ammonium cyanate is urea'

100% atom economy;
No reagent, no solvent

'Study the past, if you would define the future' - Confucius



Augustus Kekulé
1829-1886



Dmitri Mendeleev
1834-1907



Alfred Werner
1866-1919



Adolf von Baeyer
1835-1917



Wilhelm Oswald
1853-1932



Victor Grignard
1871-1935



G. N. Lewis
1875-1946

INTERNATIONAL YEAR OF THE PERIODIC TABLE -2019



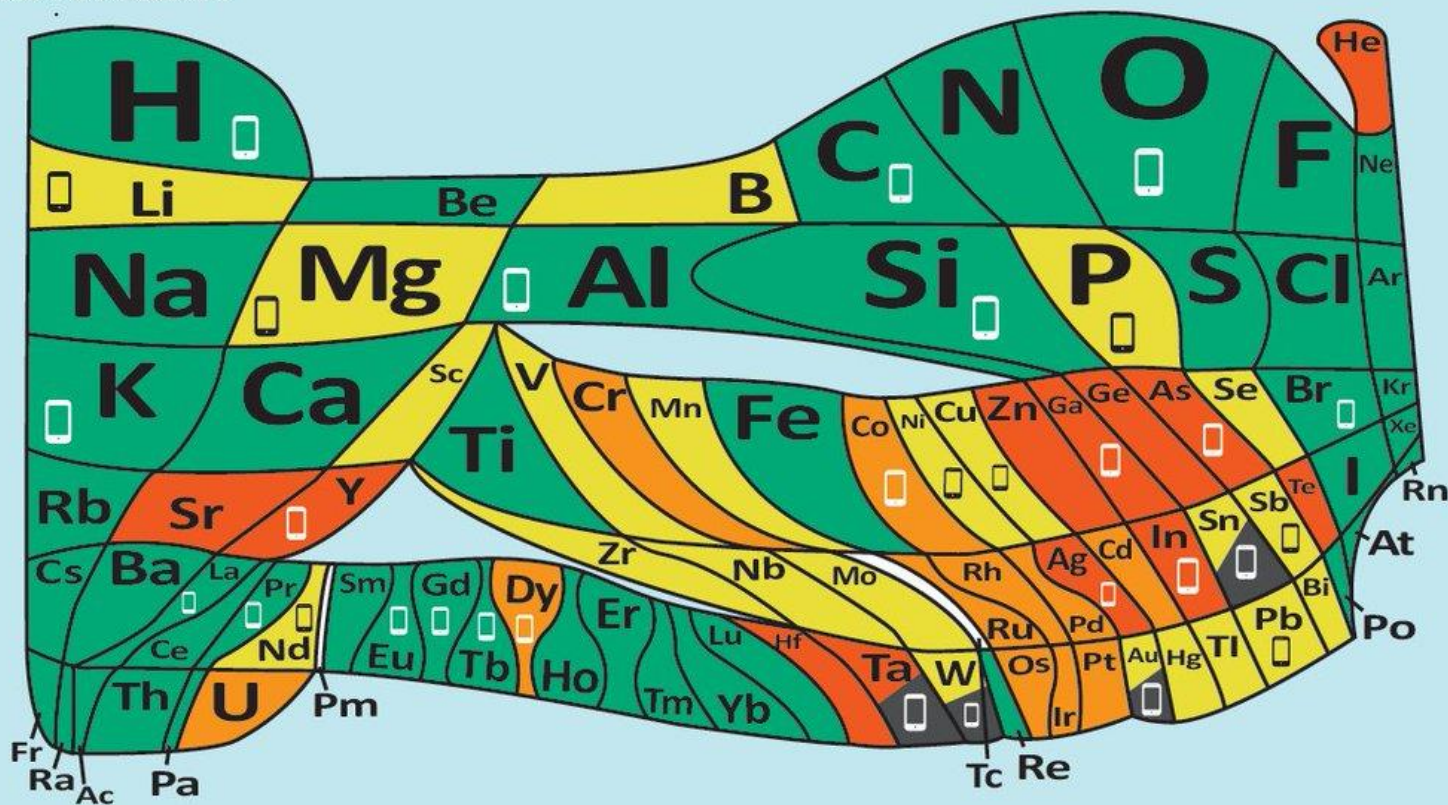
United Nations
Educational, Scientific and
Cultural Organization



International Year
of the Periodic Table
of Chemical Elements

The 90 natural elements that make up everything

How much is there? Is that enough?

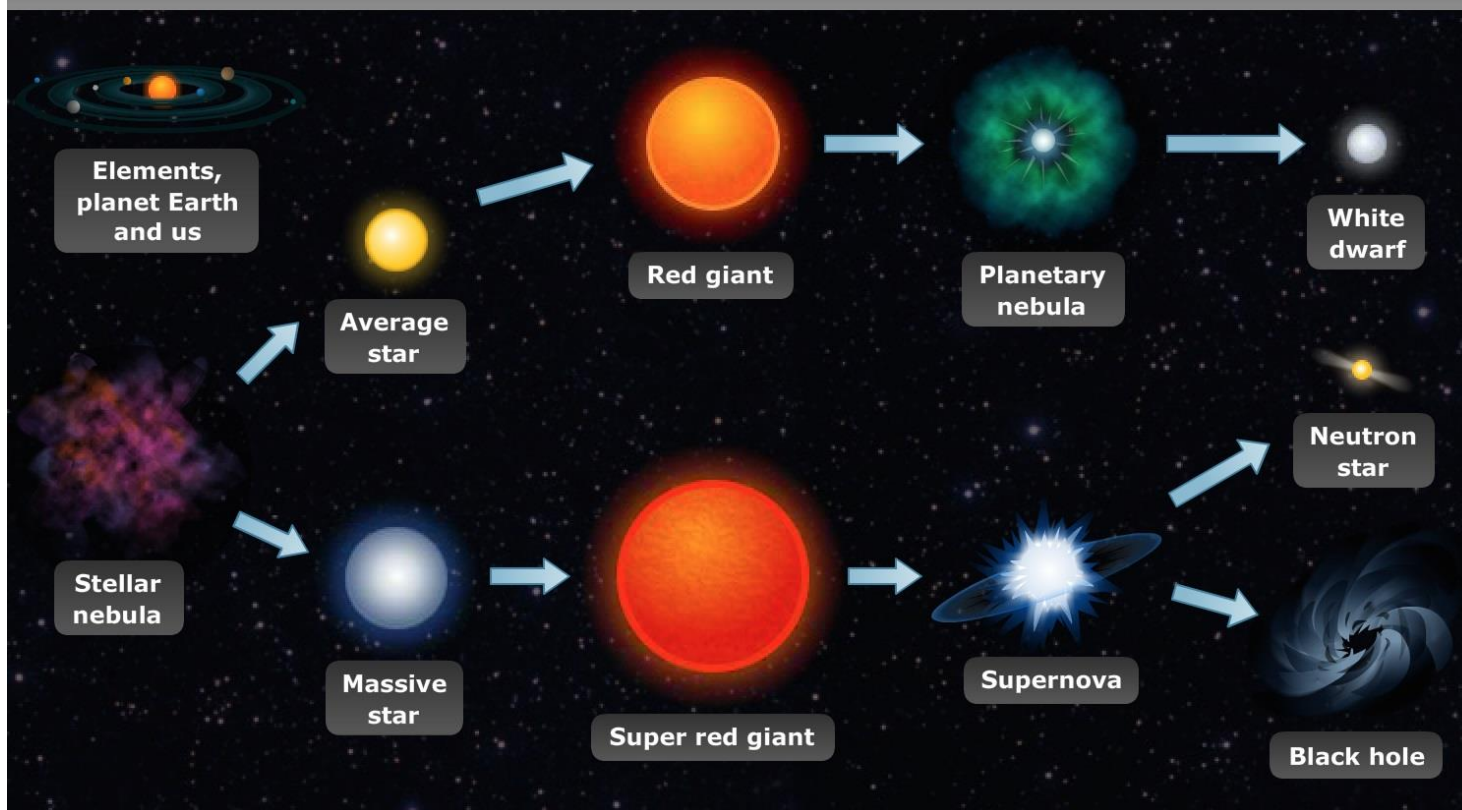


- Serious threat in the next 100 years
- Rising threat from increased use
- Limited availability, future risk to supply
- Plentiful Supply
- Synthetic
- From conflict minerals
- Elements used in a smart phone

INTERNATIONAL YEAR OF THE PERIODIC TABLE -2019

Elemental (Geological) resources (~14 Bn years old) on our planet are finite and irreplaceable.

UNIVERSAL ELEMENT FORMATION



100 second after the 'Big Bang', the universe expanded and reached the temperature of one billion Kelvin (10^9 K).

S. A. Matlin, H. Hopf, A. Krief, G. Mehta, *Current Science* **2019**, 116, 7. (Editorial)

S. A. Matlin, G. Mehta, H. Hopf, A. Krief, *Eur. J. Inorg. Chem.* <https://doi.org/10.1002/ejic.201801409>



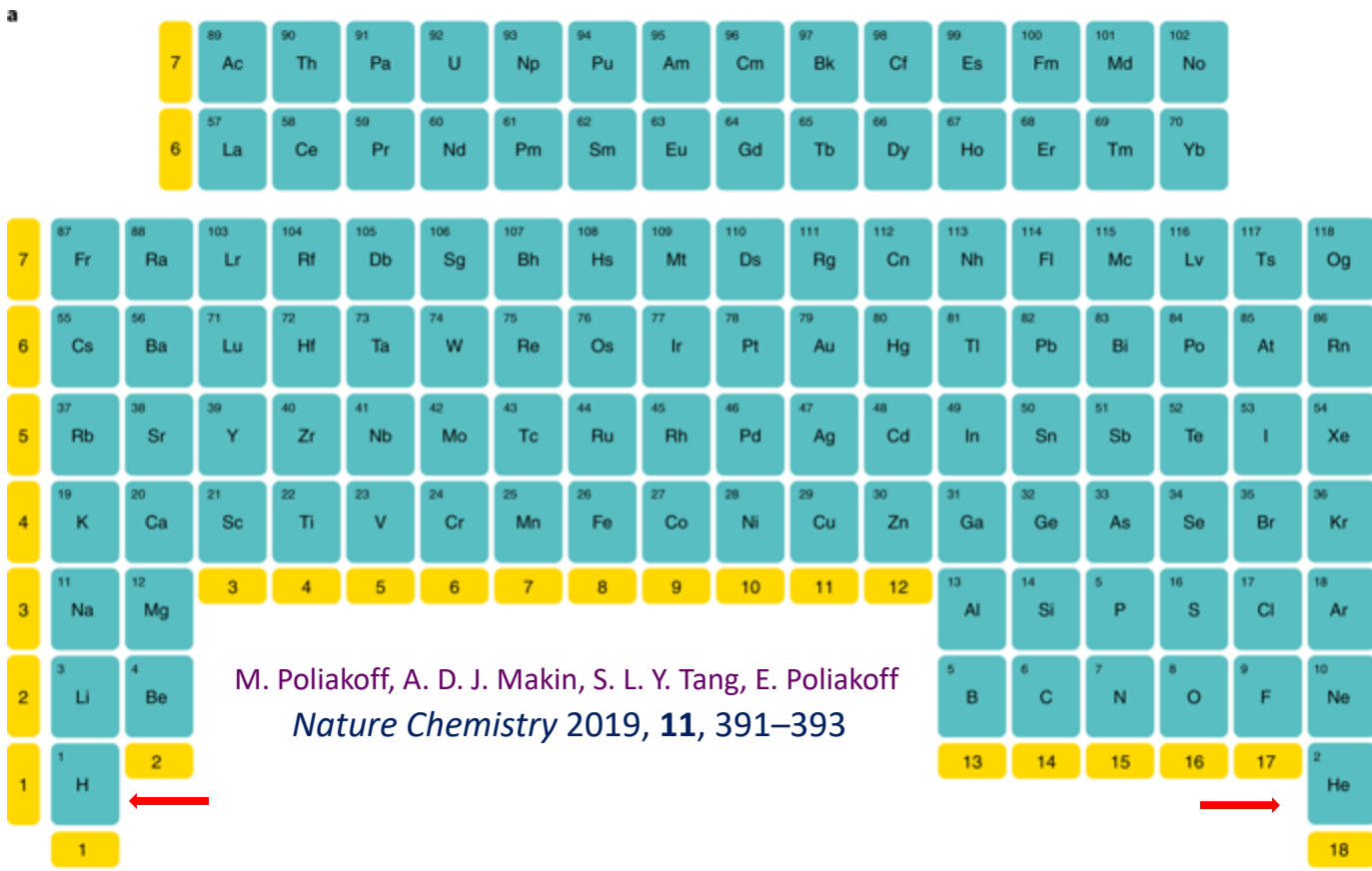
PERIODIC TABLE OF CHEMICAL ELEMENTS

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	* 72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	* 104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			* 58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
			* 90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	



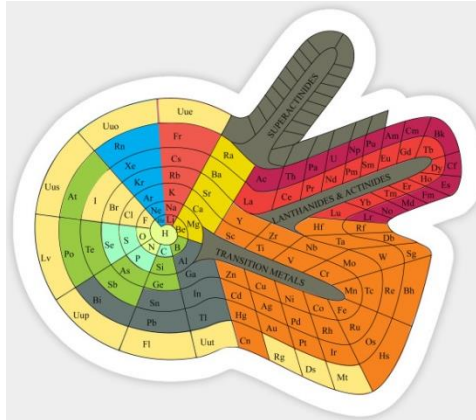
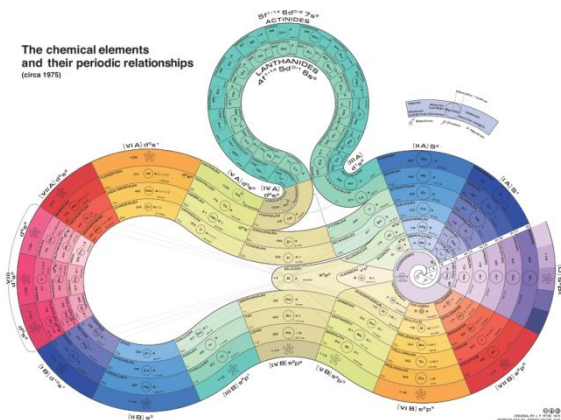
A new (crazy?) wave of Periodic Tables

Inverted Periodic Table

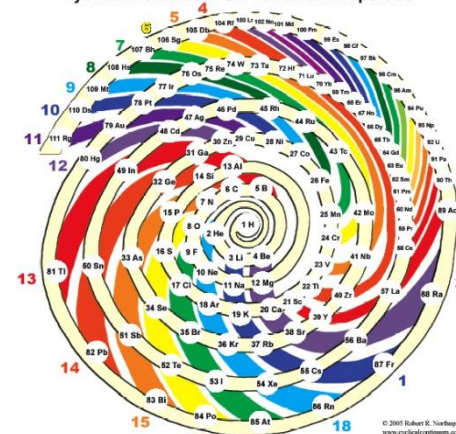


In the digital age over 100 periodic Tables proposed !!!

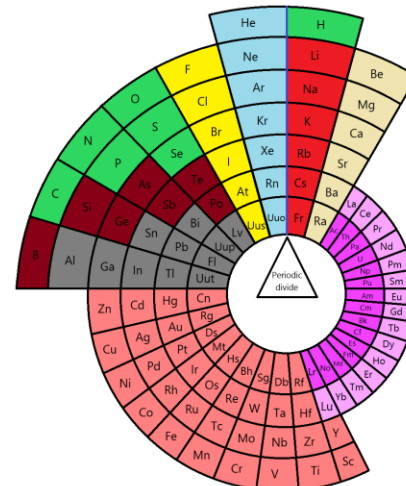
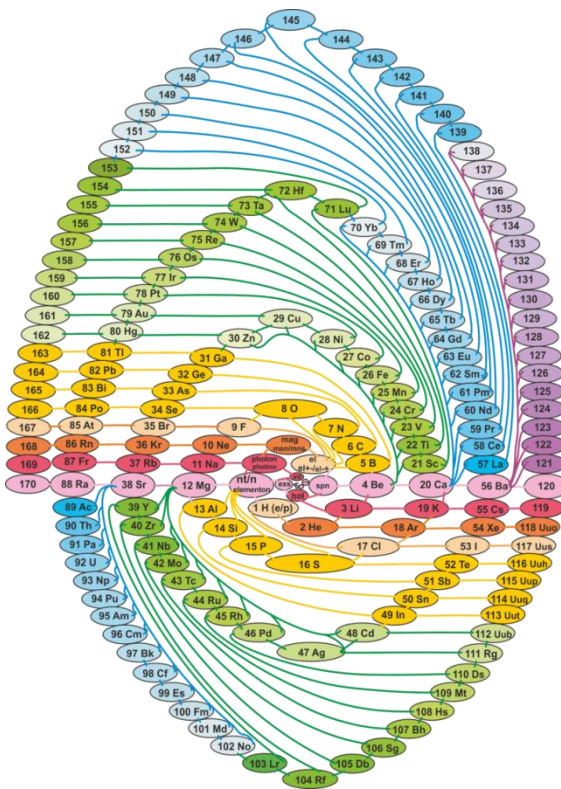
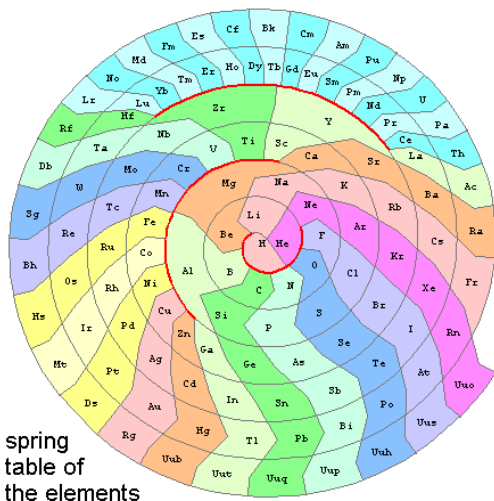
The chemical elements and their periodic relationships (circa 1975)



Cyclical Continuum of Elemental Properties



spring table of the elements



The periodic table of the elements of green and sustainable chemistry

Socio-economic

Green Chemistry and processing

Enabling systems/conditions

Noble Goals

1 A Appropriate Technologies for the Developing World	4 Dd Design to Avoid Dependency	5 B Biomimicry	6 Cb Life Cycle Cost-Benefit Analysis	7 Ae Atom Economy	8 Pr Extended Producer Responsibility	9 Ea Epidemiological Analysis and Ecosystem Health	10 P Design for Posterity													
3 Cw Chemistry for Wellness	11 Sw Access to Safe and Reliable Water	19 Bf Chemistry for Benign Food Production and Nutrition	20 Tc Transparency for Chemical Communication	21 Wu Waste Material Utilization and Valorization	22 Sa Molecular Self-Assembly	23 Ru Reduce Use of Hazardous Materials	24 Dg Design Guidelines	25 Aq Aqueous and Biobased Solvents	26 Ee Energy and Material Efficient Synthesis and Processing	27 Ib Integrated Biorefinery	28 E Enzymes	29 Bm Benign Metalloids	30 Sn Sensors	31 Bd Benign by Design	32 Hc Harm Charge / Carbon Tax	33 Ff F-Factor	34 Ct Chemical Transparency	35 Lc Life Cycle Assessment	36 Z Zero Waste	
37 J Ensure Environmental Justice, Security, and Equitable Opportunities	38 Cs Chemistry for Sustainable Building and Buildings	39 Op One-Pot Synthesis	40 Ip Integrated Processes	41 Gc In-Situ Generation & Consumption of Hazardous Materials	42 Cm Computational Models	43 Il Ionic Liquids / Non-Volatile Solvents	44 R Renewable / Carbon-Free Energy Inputs	45 C Carbon Dioxide and other C1 Feedstocks	46 Ac Earth Abundant Metal Catalysis	47 Md Molecular Degradation Triggers	48 Co In-Process Control and Optimization	49 Ie Industrial Ecology	50 Dc Depletion Charge	51 Ql Qualitative Metrics	52 Cl Chemical Leasing	53 So Solvent Selection Screens	54 Fi Chemistry is Equitable and Fully Inclusive			
55 Pc Chemistry to Preserve Natural Carbon and Other Biogeochemical Cycles	56 Ic An Individual's Molecular Code Belongs to that Individual	57 Pi Process Intensification	58 As Additive Synthesis	59 Ch C-H Bond Functionalization	60 Ba Bioavailability / ADME	61 Sc Sub- and Super-Critical Fluids	62 Es Energy Storage / Transmission Materials	63 Sb Synthetic Biology	64 Ht Heterogeneous Catalysis	65 Dp Degradable Polymers and Other Materials	66 Ex Exposome	67 Tg Trans-Generational Design	68 Rf Sustained Research Funding	69 Qn Quantitative Metrics	70 Se Self-Enforcing Regulations	71 Cf Chemical Footprinting	72 De Benefits Distributed Equitably			
73 Wo No Chemicals of War or Oppression	74 Nc Molecular Codes of Nature Belong to the World	75 Ss Self-Separation	76 W Non-Covalent Derivatives/ Weal: Force Transformation	77 Is Inherent Safety and Security	78 Ts High Throughput Screening (Empirical / In Vivo / In Vitro)	79 S "Smart" Solvents (Obedient, Tunable)	80 V Waste Energy Utilization and Valorization	81 Bt Biologically-Enabled Transformation	82 Hm Homogeneous Catalysis	83 Pd Prediction and Design Tools	84 Ga Green Analytical Chemistry	85 Be Bio-Based Economy	86 Ci Capital Investment	87 Bb Chemical Body Burden	88 I Innovation Ecosystem - Translation from Lab to Commerce	89 Et Education in Toxicology and Systems Thinking	90 K Extraordinary Chemical Knowledge Comes With Extraordinary Responsibility			

- Prevent Waste
- Atom Economy
- Less Hazardous Synthesis
- Molecular Design
- Solvents/Aux
- Energy
- Renewable Feedstocks
- Catalysis
- Degradation
- Measurement and Awareness

- Conceptual Frameworks
- Economics and Market Forces
- Metrics
- Policies and Regulations
- Tools

Resources - Resources - Resources

“Human history is a story of innovation and increased efficiency, but also of relentless depletion of Earth’s resources.”

- *Václav Smil*

Listen to the Scientists...

- Greta Thunberg –Testimony before US Congress

.....How dare you?

“...all you can talk about is money and fairy tales of eternal economic growth. How dare you?”

- Greta Thunberg

Why are chemical resources basic to the sustainability of our planet?

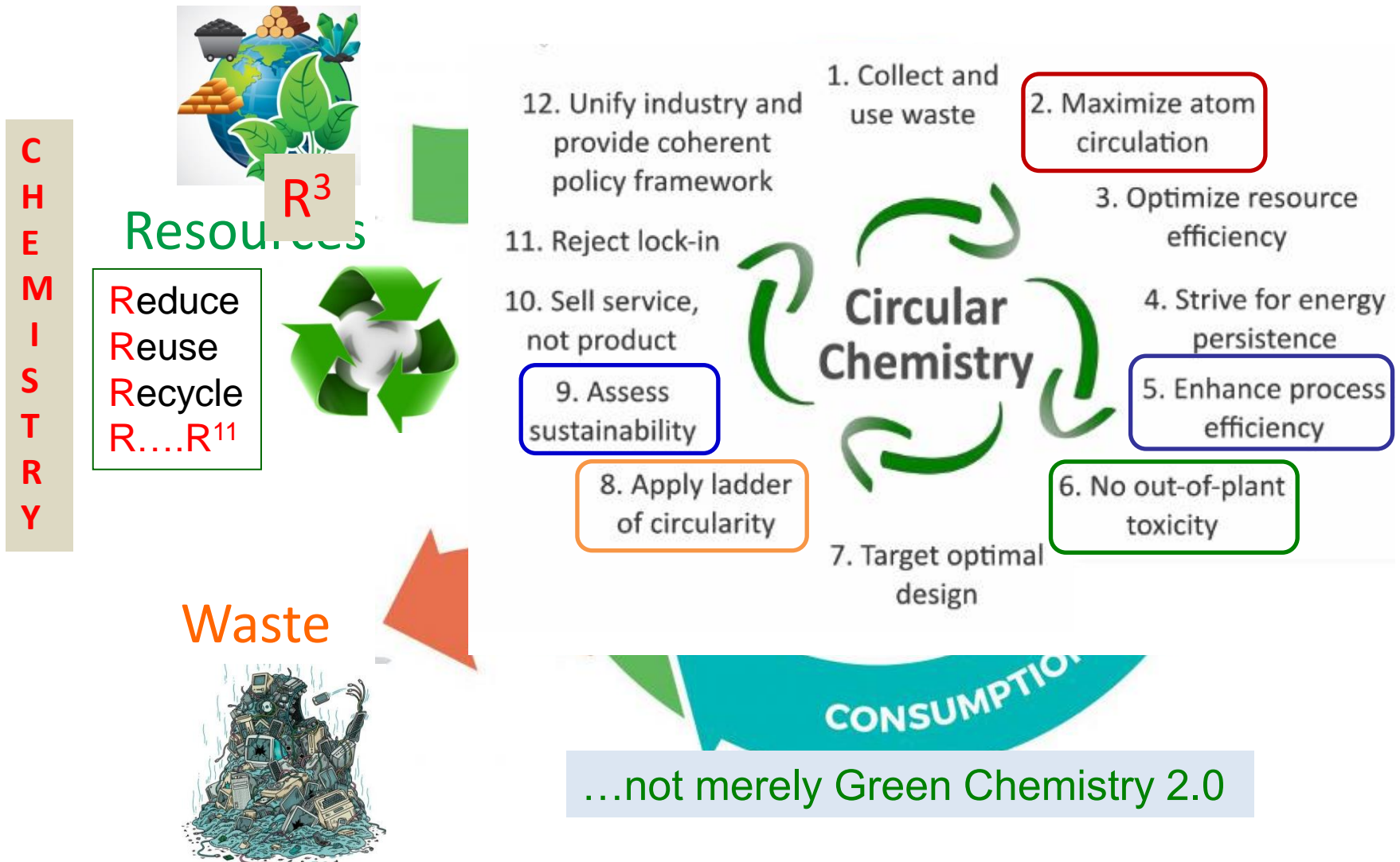
“There is no author whose books I look forward to more than Vaclav Smil.”

—BILL GATES

VACLAV
SMIL
GROWTH
FROM MICROORGANISMS TO MEGACITIES



From 'Circular Economy' to 'Circular Chemistry'



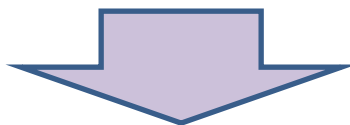
Geng, Sarkis, Bleischwitz, *Nature*, **2019**, 565, 153- 55

Keize, Bakker, Sloopweg, *Nature Chemistry*, **2019**, 11, 190



Chemistry: Securing a Sustainable Future

Recognise the end of - make, use, dispose era;
onset of - reuse, refurbish, re- and upcycle era

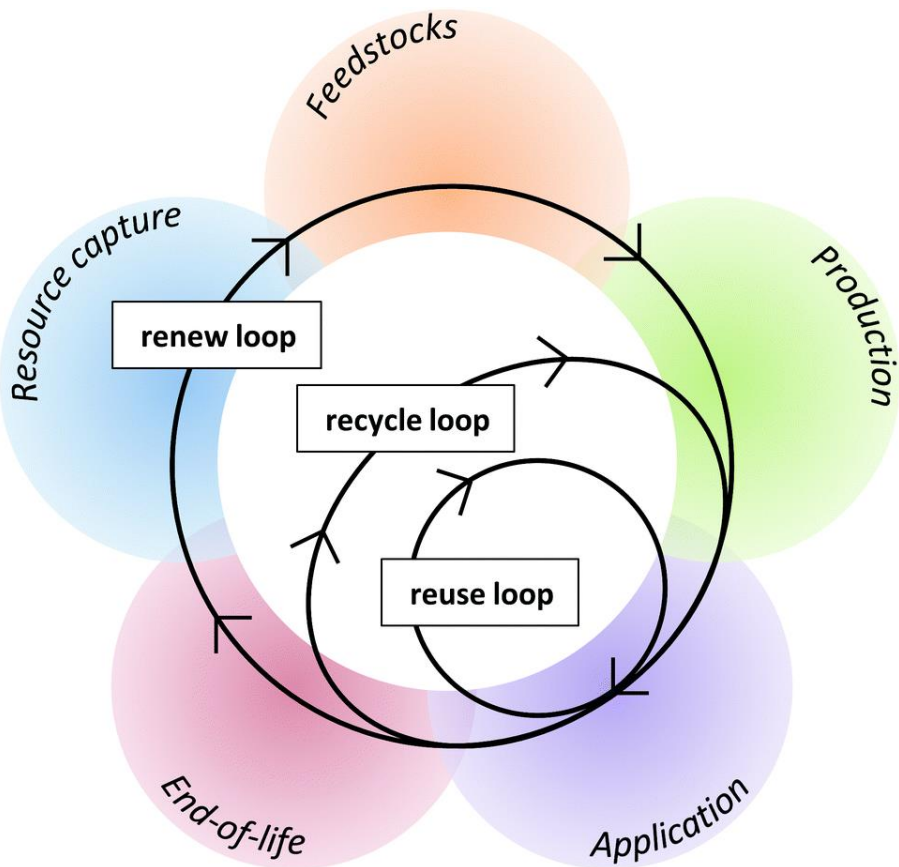


Cradle to Cradle 'C2C' chemical design

... design concepts in which ...products are created according to the principles of an ideal circular economy, beyond the conventional recycling, inspired by eco-efficiency and sustainability .

“There is no such thing as ‘away’. When we throw anything away it must go somewhere.”

Need innovative approaches in chemistry



Some good practices and home truths

Chemical and material design for zero waste

A product is also a resource equal to a raw material

End-to-end , systems based approach

One 'Green' step in a process is inadequate

Digital processing/manufacturing

Shared platform between bench & process chemist

Seamless synergy between Chem. Eng. and chemists

K. Rossen, *Greening organic chemistry with process chemistry*, *J. Org. Chem.* **2019**, *84*, 4580-4582

James H. Clark *et al.* *Green Chemistry*, **2016**, *18*, 3914-3934

Material use in perpetuity

Possible scenarios.....

- Fixed allocation of material to every individual
- Material purpose defined
- Digitalization, AI and robotics, 3D-printing
- Real-time chemical transformation and delivery



Utopian ??????

Break for reflection





Molecular level view of everything and molecular creation is central to chemistry

Molecular machinesmolecular gastronomy....molecular condoms*!

*PNAS, May 2017



Chemists create their own molecular cosmos

“Chemistry has become today the science of bodies that do not exist”

- Auguste Laurent - 1854



“The beauty of chemistry is that I can design my own molecular world.”

*Ben L. Feringa, NL chemistry 2016
Molecular Sciences Professor,
University of Groningen*

Credit Shutterstock

C&EN

..Chemistry creates its subject. This creative ability, similar to that of arts, essentially distinguishes chemistry among the natural and historical sciences.

- M. Berthelot - 19th century

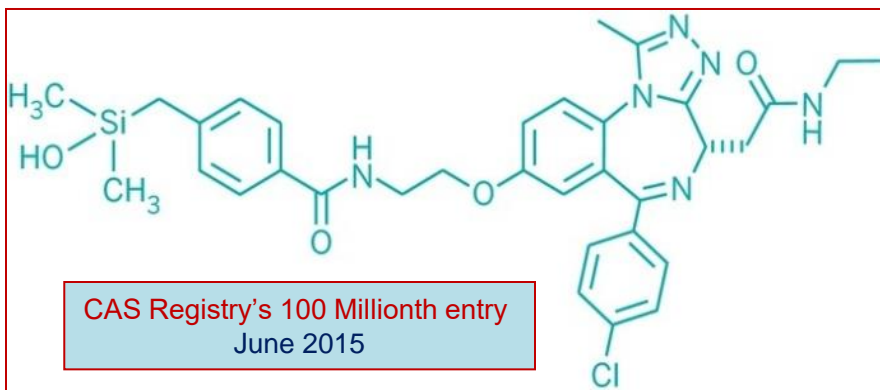


Sizing the molecular cosmos

10^{80} to 10^{200} unique chemical structures possible

That is not far from infinity; impractical?

...and there is not enough mass in the Universe !



A galloping pace..
145 M in CA Registry, 2018;
many millions buried in patents;
best estimate ~ 0.5 billion NME's
Only a fraction is useful!

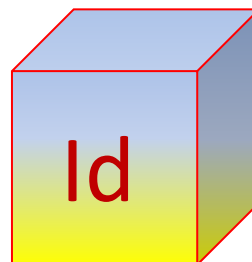
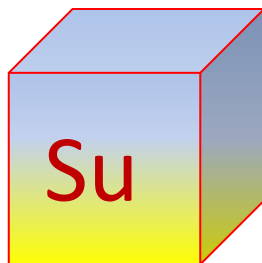
Chemistry is also the science of the possible

Just about any chemical can be accessed today
butshould we ?

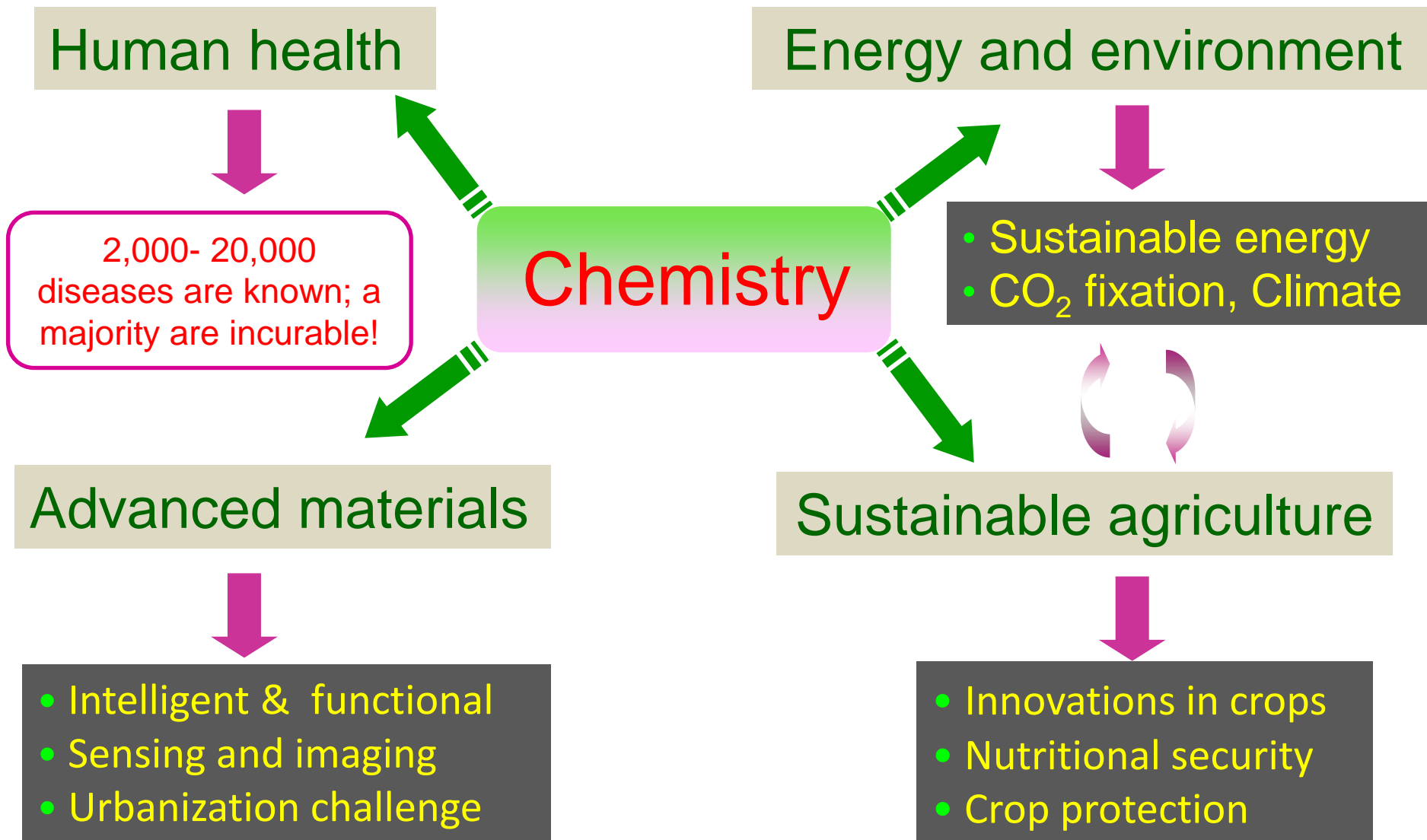
Mantra to remember...

Resource only what is needed for human advancement and well-being;
in risk free, non-hazardous way with minimal environmental footprint.

Adopt new symbols – Beyond the Periodic Table



Pivotal role.....on the path to sustainability



New opportunities, challenges and promises to keep;
Chemistry can!

A silhouette of two people, an adult and a child, looking through a large telescope mounted on a tripod. The scene is set against a sunset or sunrise sky with a gradient from orange to blue. The adult is pointing towards the sky, and the child is looking through the telescope.

Sustainability Science

A few take home messages & urgings

Chemistry's future as an ethical science

- ACS has created a **Global Code of Ethics (GCCE)** for chemists based on the Hague Ethical Guidelines¹;
- Ethical concerns must encompass **responsible practice of chemistry** and make a strong pitch for **environment and sustainability**;
- Adherence to method and values of science – **embrace scientific temper** ;
- Ethical concerns to expand beyond the traditional issues about **research practices** and transparency; personal conduct & practice of collegiality;

Value diversity²

- Ingrain ethical values as an integral part of chemistry education.

¹ <https://www.acs.org/content/dam/acsorg/global/international/scifreedom/global-chemists-code-of-ethics.pdf>

² G. Mehta, V. W. Yam, A. Krief, H. Hopf, S. A. Matlin, *Angew. Chem. Int. Ed.* **2018**, *57*, 14690-14698

Inculcate cultural competencies

1 International Edition: DOI: 10.1002/anie.201900057

2 German Edition: DOI: 10.1002/ange.201900057

3
4 **The Need for Cultural Competence in**
5 **Science: A Practical Approach to Enhancing**
6 **Equality, Diversity, and Inclusion**
7
8
9

10 *Stephen A. Matlin,* Vivian W. W. Yam,* Goverdhan Mehta, Alain Krief, and*
11 *Henning Hopf* *Angewandte Chemie, Intl. Ed.* 2019, 58(10), 2912.
12
13

Research integrity is more about culture than compliance

- Embed integrity in research culture.
- CC is the best antidote against 'Fake-philia' & 'Dichotomania'

In shaping success – a scientist's persona matters.....

A tale of two great chemists.



I. Langmuir
1881-1954

Langmuir won a Nobel Prize for surface chemistry and hobnobbed with the likes of Albert Einstein and Niels Bohr. He was very interactive, appeared on the cover of magazines and made millions of dollars for and from a company like General Electric.

Harmonize your persona with creative instincts?



G. N. Lewis
1875-1946

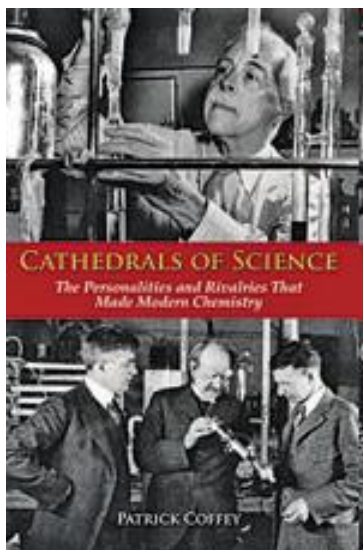
Lewis built the UC Berkeley, chemistry into the best in the world but lacking a Nobel Prize, became a bitter hermit. One afternoon in 1946, panicked graduate students discovered Lewis lying in a laboratory that smelled like almonds– HCN?. Dead!

“If there was a manual on how not to win a Nobel Prize, Lewis could have written it.”

Ref: Cathedrals of Science: The Personalities and Rivalries That Made Modern Chemistry,
Patrick Coffey, Oxford University Press, 2008

The ugly terrain of scientific ambition..... Chemist's are no exception

Chemists are human: Also afflicted by avoidable rivalries



Lewis and Langmuir



Svante Arrhenius
1859-1927
N.L. 1903



Walther Nernst
1864-1941
N.L. 1920

“...His legacy secure, Arrhenius, as chair of the Nobel Institute for Physical Chemistry, in Stockholm, spent his life blocking the prize nominations of rivals like Nernst, who in turn blocked Lewis...”

Respect and accommodate the scientific contributions and creativity of peers and competitors

But, there is a better way.....inspiring colleagues

- Letter from Derek Barton (NL 1969) to R. B. Woodward (NL 1965) on 16 Dec 1969

“Greetings from Stockholm..... This seems also a good moment to thank you for the remarkable inspiration you gave me in 1949–1950. **You transported me at that time from one world of chemistry to another which I had not imagined to exist.**”



D. H. R. Barton
1918 -1998



R. B. Woodward
1917 -1979

Ref: Working with Sir Derek. H. R. Barton – “Chemistry, through chemistry and for chemistry”

J.I. Seeman. *Tetrahedron* 2019, 75, 57-69, <https://doi.org/10.1016/j.tet.2018.11.004>

A strong pitch for humility



Marie Skłodowska Curie
1867-1934

A legacy of passion and humility...

Albert Einstein is reported to have remarked that Mme. Curie was probably the only person who was **not corrupted by the fame that she had won.**



Acharya P. C. Ray
1861-1944

Father of chemistry and chemical industry in India

One who could integrate ideas with idealism;
A venerable legacy of humility and patriotism



Daniel Schechtman
1941-

" A good scientist is a humble scientist! "

- Dan Schechtman , Nobel Laureate 2011

Board the 'Outlook' express

- Always look around - treat chemistry knowledge and learning as holistic
 - Great to be focused but not a 'frog in the well' or 'ostrich-like'!
 - Surf the horizon – develop the instinct to grasp the big picture
 - Be mindful of the gap between visioning/dreaming and realizing
 - Think chemistry as a science for the benefit of all – from ideas to products
-

“I have always tried to avoid following the flock. I have worked in many fields, but as soon as these fields became popular, I have moved on. I have made the joke of saying that if you cannot remember all the published papers in the field you are working in, then it is time to move on.”

- D. H. R Barton, N.L Chemistry 1969

Thank you for your kind attention

A big thank you to Eli-Lilly, Jubilant Bhartia Foundation and Dr. Reddy's Research Laboratory for research support.



Lilly



A crystal of aspirin

Chemistry is stunningly beautiful!

Thank you for your kind attention

Chemistry promotion with Professors Henning Hopf, Stephen Matlin and Alain Krief - **(C4S)**

supported by IOCD, Syngenta, Royal Society of Chemistry (RSC), GDCh, DRILS and IICT



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A crystal of aspirin

Chemistry is stunningly beautiful!