Seeing the Forest While in the Trees:

Systems Thinking in Science Education

Sydney 2018 July 8-11 CONASTA 67 Spotlight On Our Future

ICCE SYDNEY | JULY 10-14, 2018 www.icce2018.org

Peter Mahaffy

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THE KING'S UNIVERSITY

Stephen Matlin

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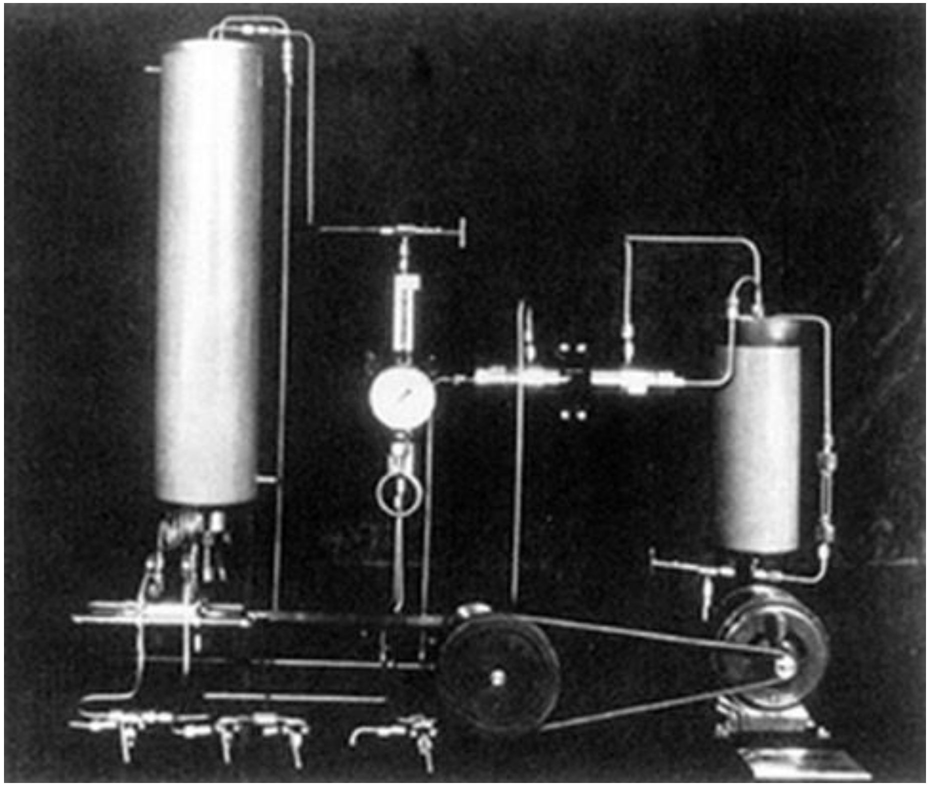
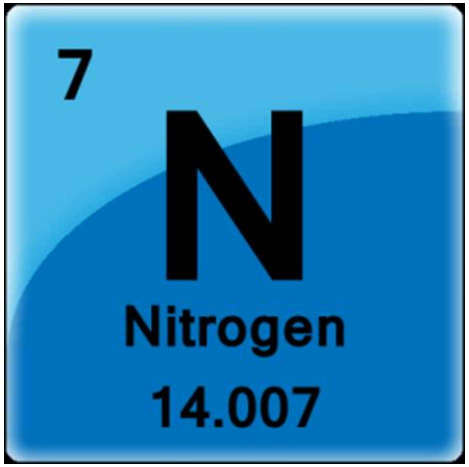
IOCD International Organization for Chemical Sciences in Development

Imperial College London

The most important technological invention of the 20th Century?

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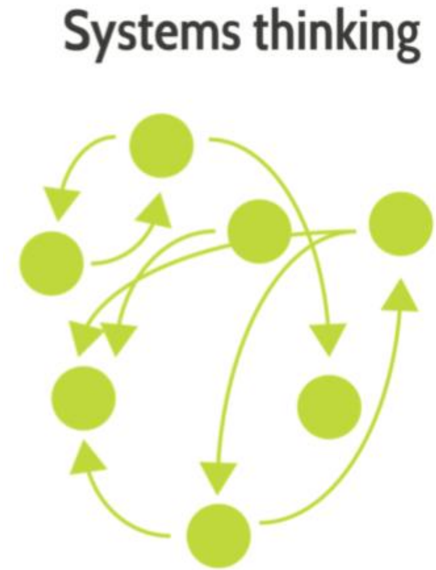
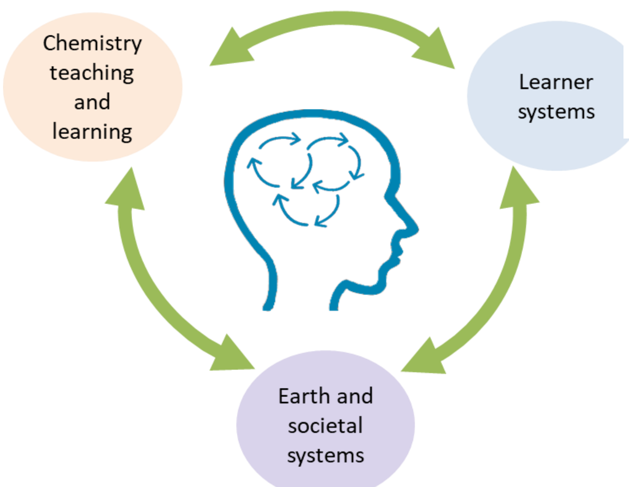
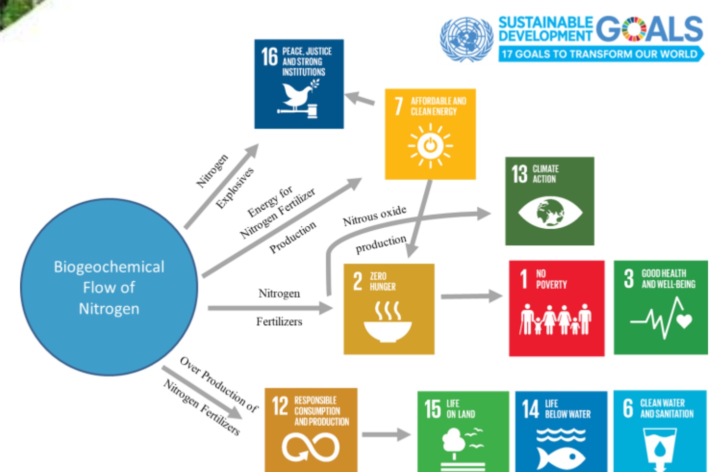

Systems thinking


Chemistry teaching and learning
Learner systems
Earth and societal systems


SUSTAINABLE DEVELOPMENT GOALS
17 GOALS TO TRANSFORM OUR WORLD
16 PEACE, JUSTICE AND STRONG INSTITUTIONS
7 AFFORDABLE AND CLEAN ENERGY
13 CLIMATE ACTION
Biogeochemical Flow of Nitrogen
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Energy for Nitrogen Fertilizer Production
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2 ZERO HUNGER
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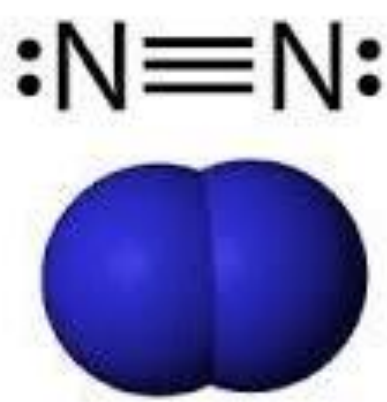
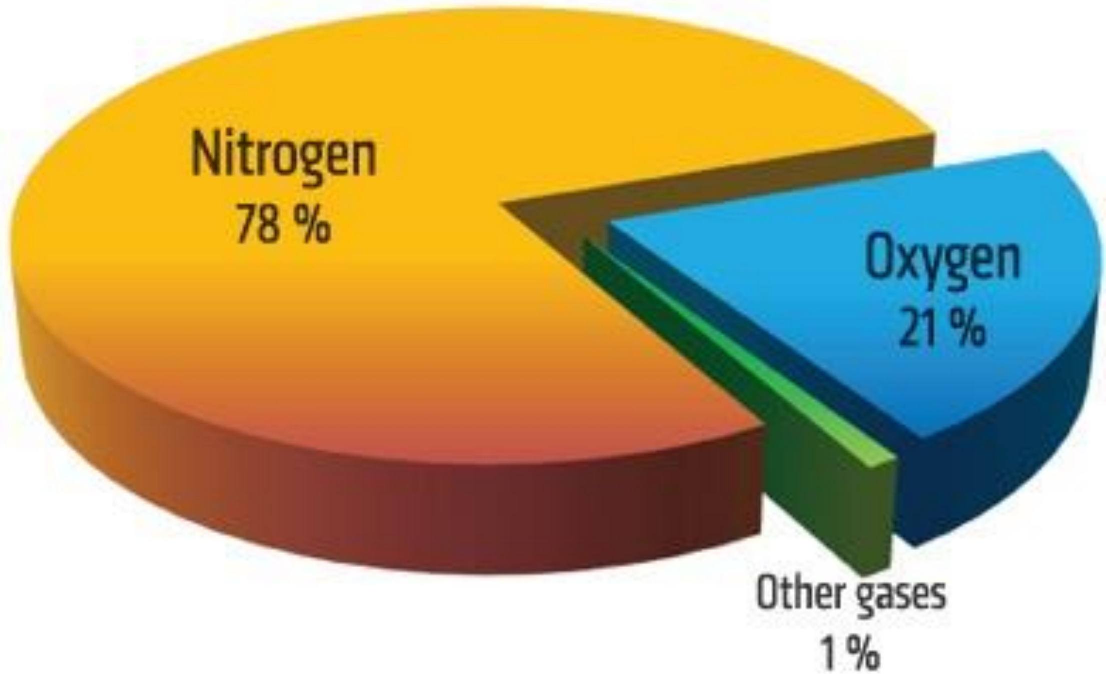
12 RESPONSIBLE CONSUMPTION AND PRODUCTION
15 LIFE ON LAND
14 LIFE BELOW WATER
6 CLEAN WATER AND SANITATION

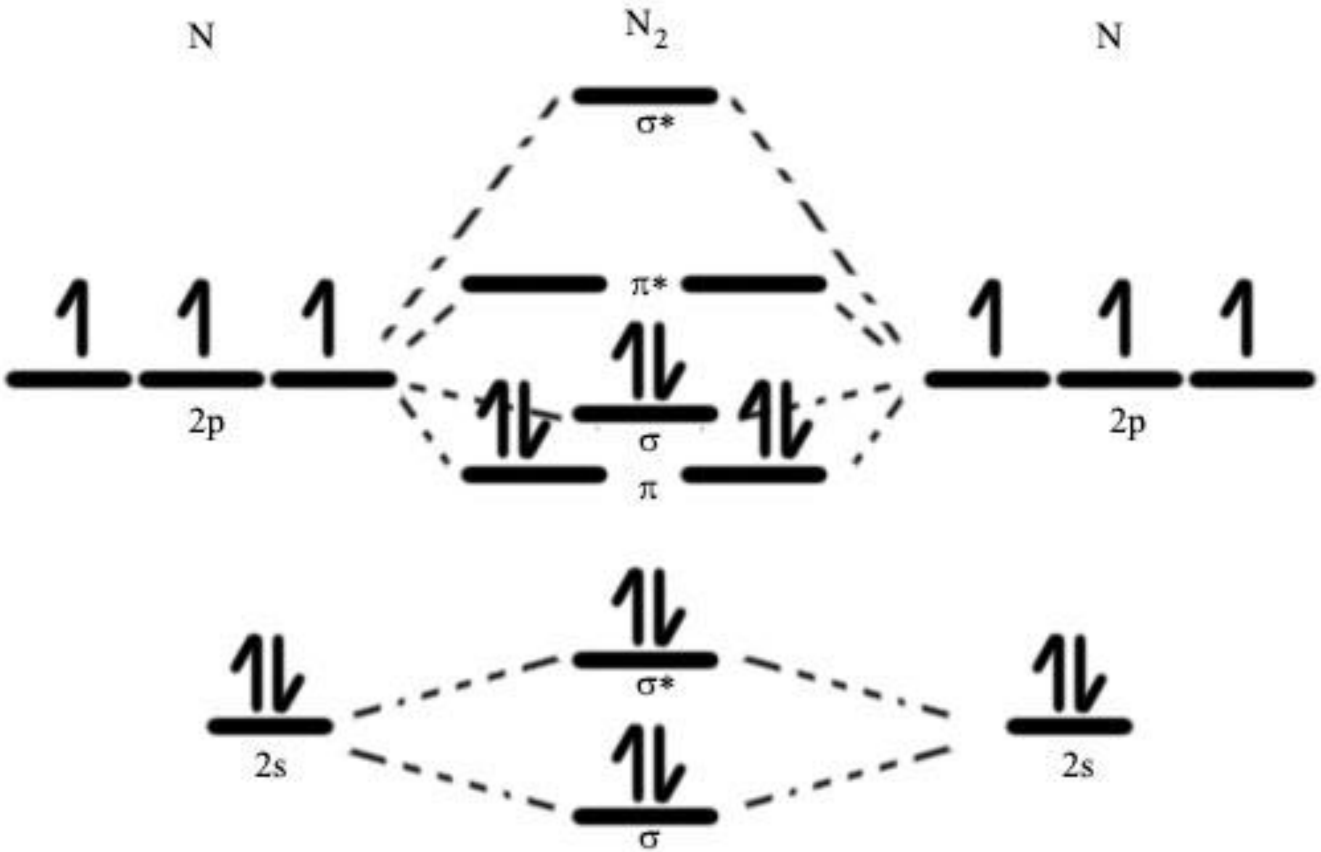
Nitrogen and its Compounds





What do students taking chemistry in your school/university learn about nitrogen and its compounds? (Learning outcomes)

Nitrogen and its Compounds



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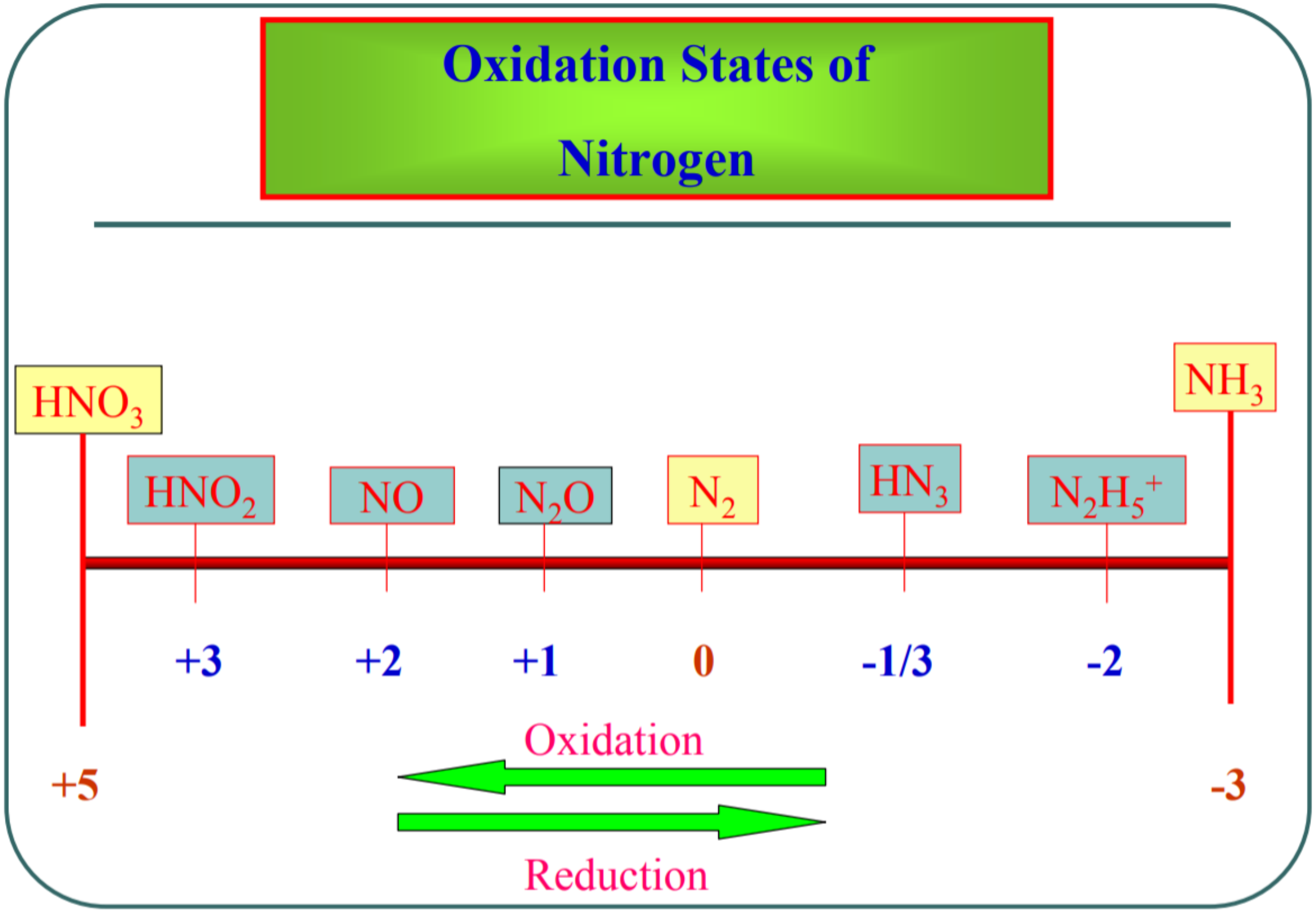

http://www.chem.tamu.edu/

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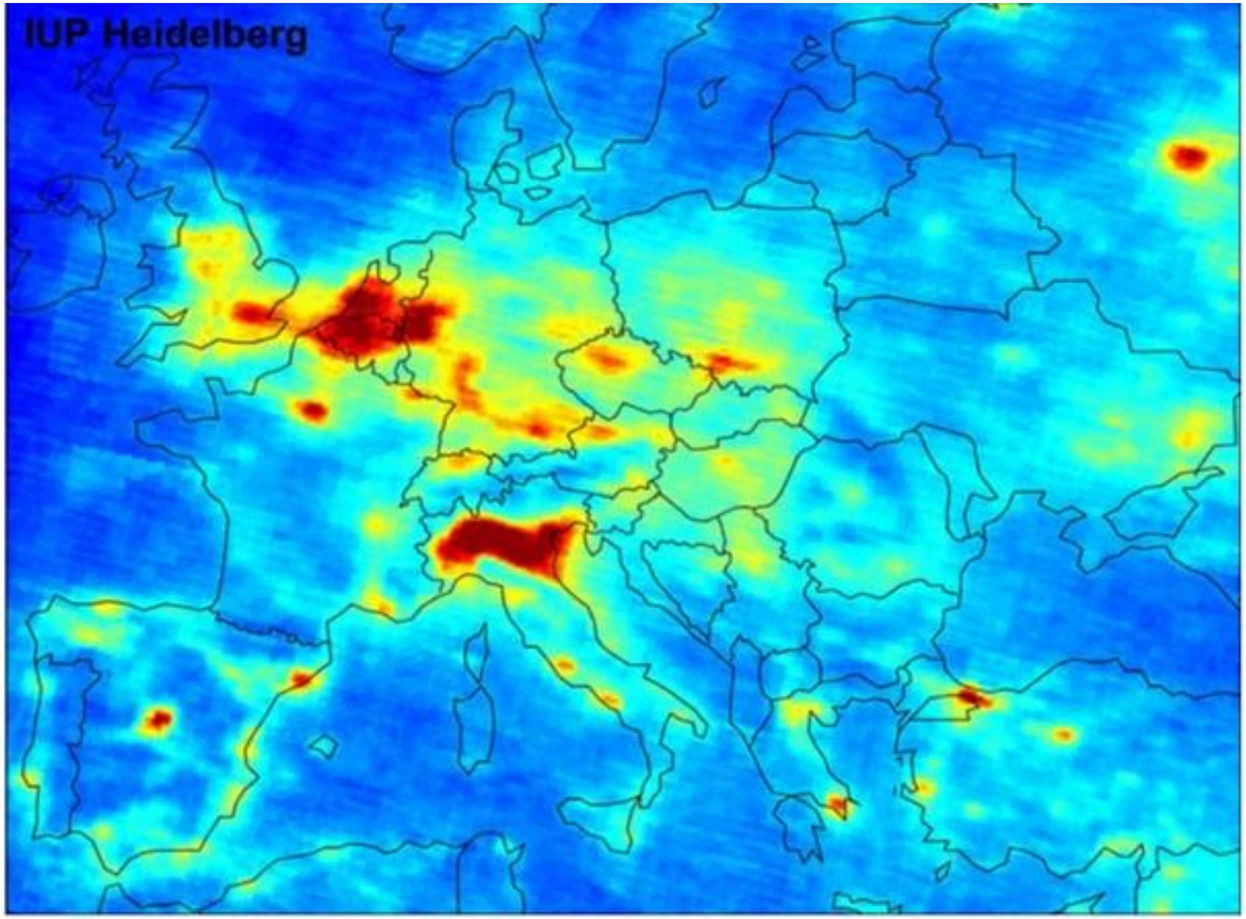


NO2 levels over Europe - zoom for detail

What do students taking chemistry in your school/university learn about nitrogen and its compounds? (Learning outcomes)

7 **N** Nitrogen 14.007

Nitrogen and its Compounds

Fritz Haber (1868–1934). Haber developed a method for combining nitrogen from the air with hydrogen to make ammonia, a valuable agricultural chemical. A biographer described him as "verbally and action-oriented rather than contemplative," and a contemporary said that his talent for gaiety and laughter was enormously appealing.

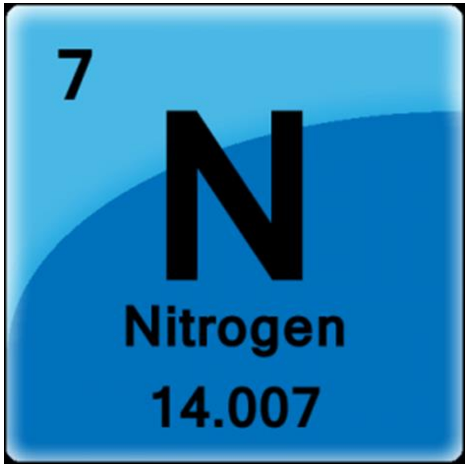
Applying Le Chatelier's Principle – The Haber Process

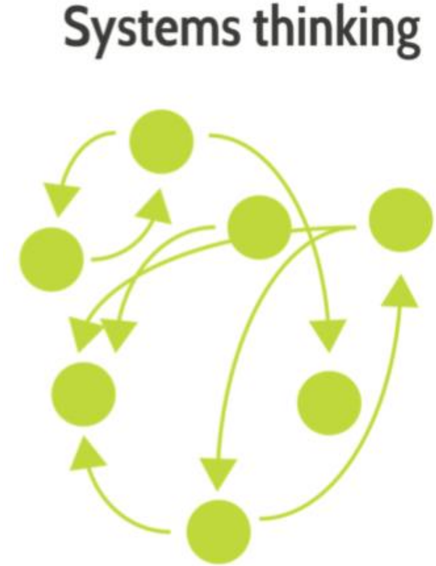
$$N_{2(g)} + 3H_{2(g)} \rightleftharpoons 2NH_{3(g)} \quad \Delta H = -92kJ$$

$$K_p = \frac{(P_{NH_3})^2}{P_{N_2} \times (P_{H_2})^3} = 6.0 \times 10^5 \text{ at } 25°C$$

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

What do students taking chemistry in your school/university learn about nitrogen and its compounds? (Learning outcomes)

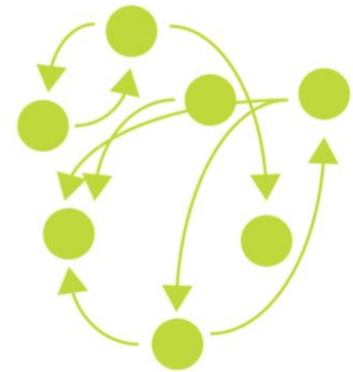




What is systems thinking?

What (on earth!) does it have to do with what students learn about nitrogen?

Systems thinking



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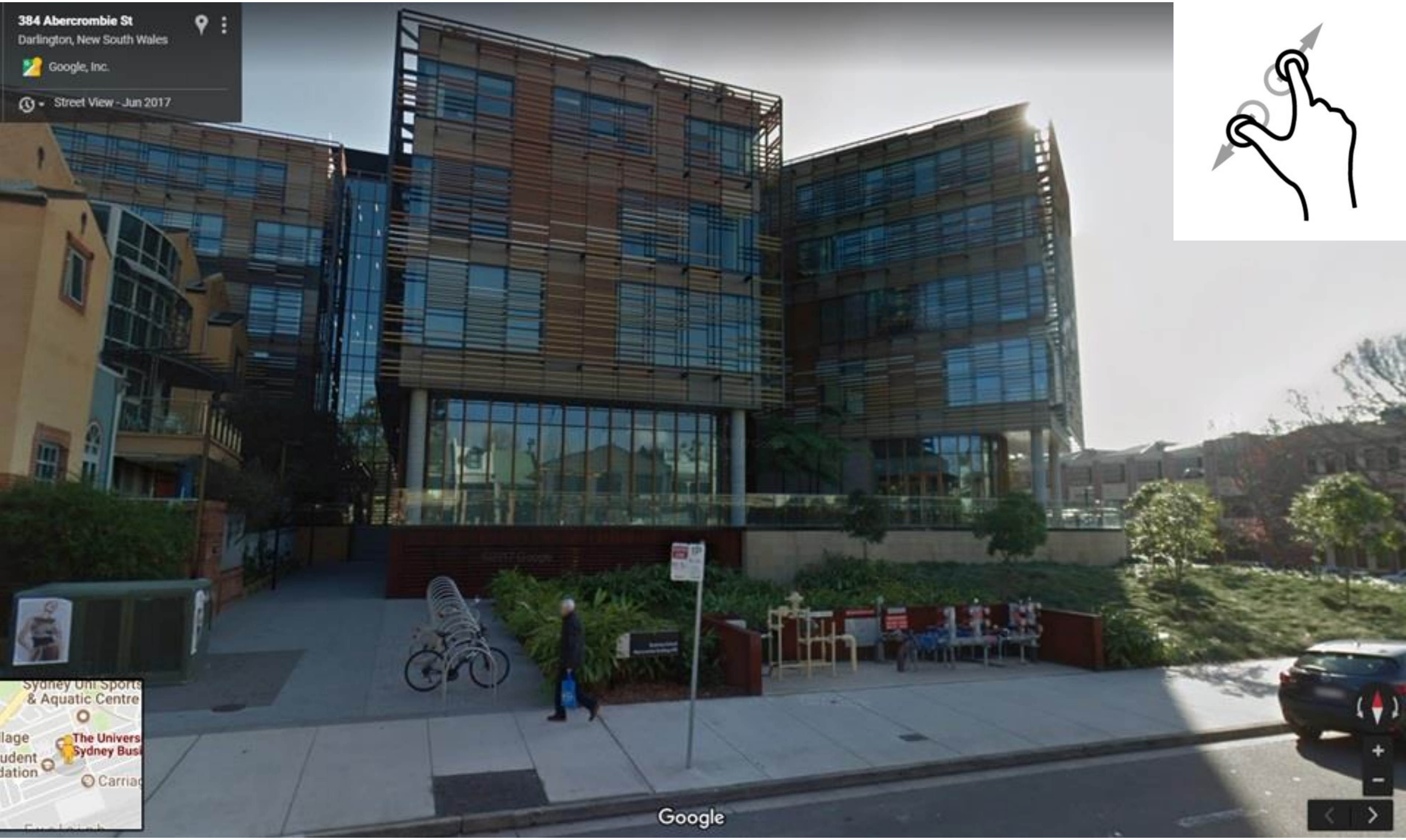
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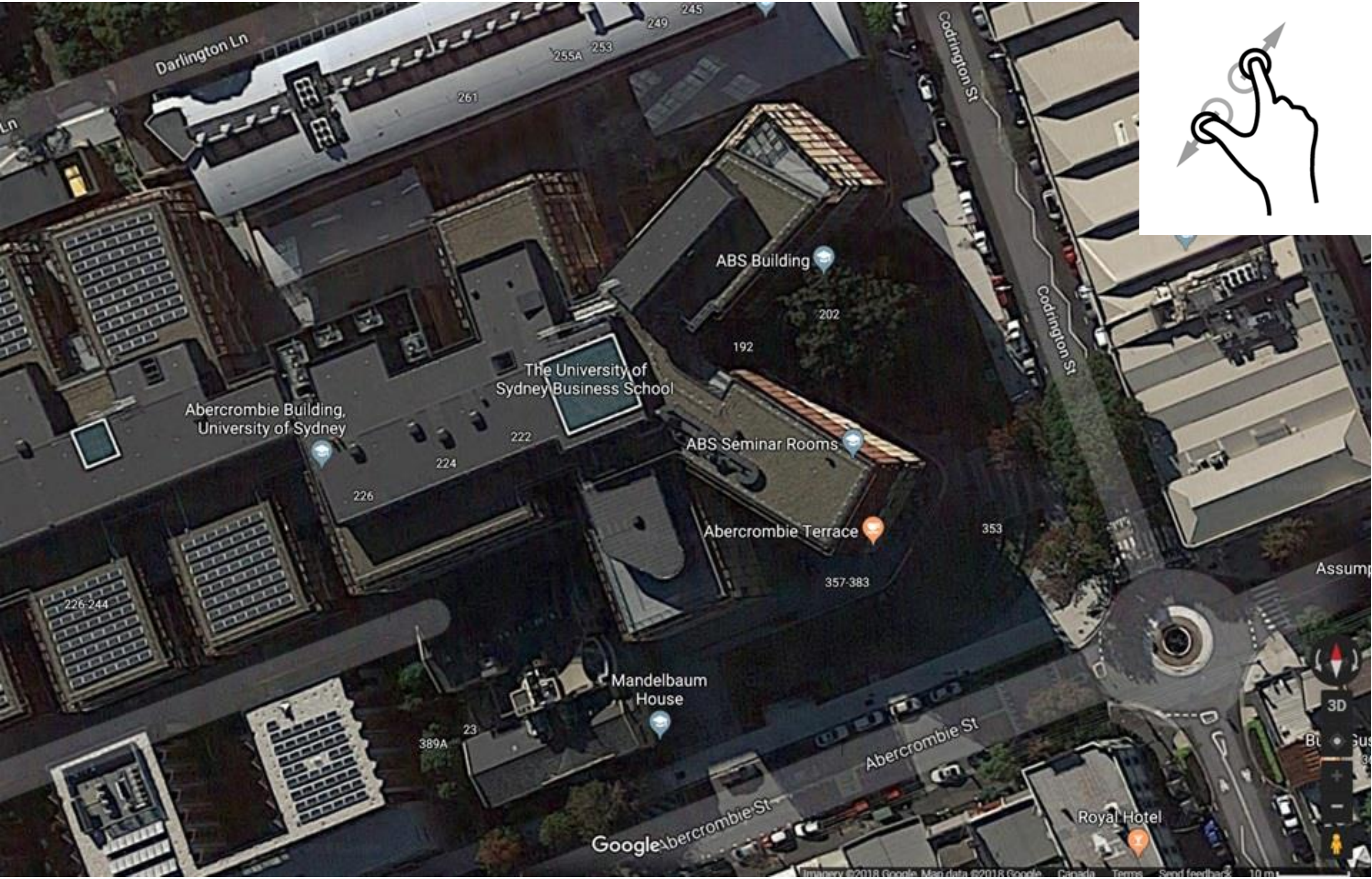
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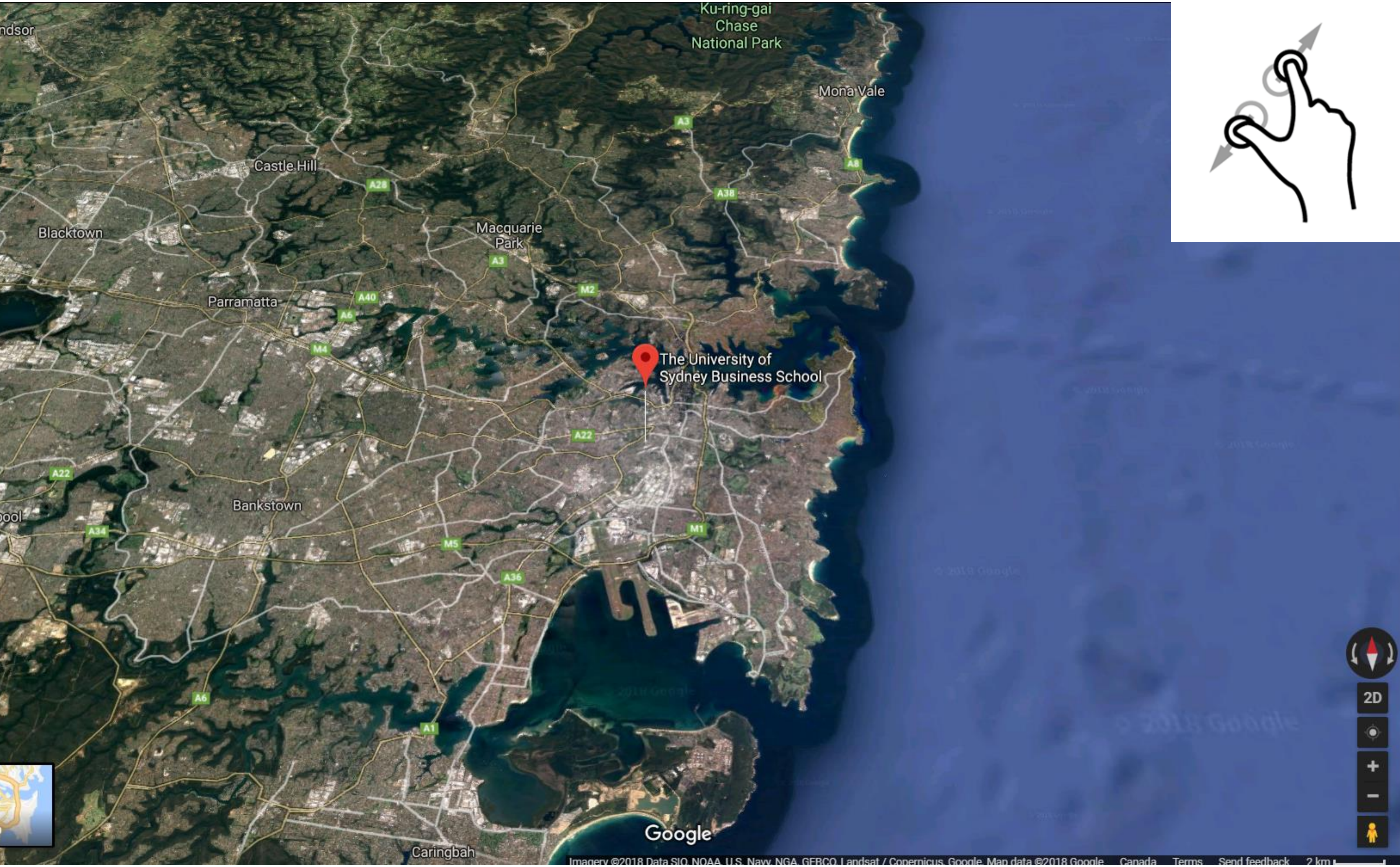
Ku-ring-gai Chase National Park
Mona Vale
Castle Hill
Blacktown
Macquarie Park
Parramatta
The University of Sydney Business School
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A34
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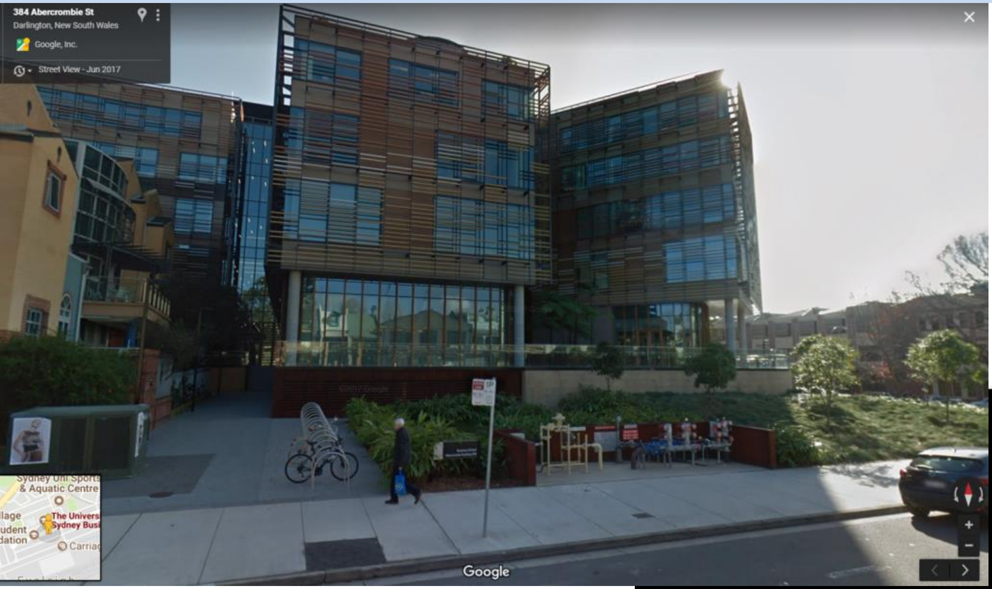
Biophysical Systems for the Conference:
A new perspective



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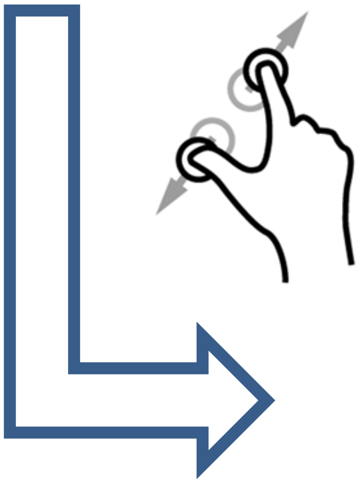

Working definitions

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

Earth & Societal Systems: Pinch to Zoom Out

Earth & Societal Systems: Pinch to Zoom Out

WELCOME TO THE ANTHROPOCENE

Quality of life for many humans has been profoundly improved by the application of chemistry

Yet multiple challenges for earth and its people are emerging

Quality of life for many humans has been profoundly improved by the application of chemistry

Unicef, South Sudan

News › World › Australasia

Great Barrier Reef can no longer be saved, Australian experts concede

'In our lifetime and on our watch, substantial areas of the Great Barrier Reef and the surroundi
ecosystems are experiencing major long-term damage'

Ian Johnston Environment Correspondent | @montaukian | 2 hours ago | 106 comments

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The need for ST in chemistry

Chemistry roles

- Fundamental physical science
  - atoms, molecules, their behaviour & transformations
- Useful science
  - valued processes and products
- Science for the benefit of society*
  - helping tackle multiple emerging global challenges: **sustainable development**…

    …BUT ***the central role for chemistry in this is not sufficiently clear or visible***

= ***a new imperative for chemistry***

* Matlin, Mehta, Hopf & Krief
- Nature Chemistry 2015, 7, 941-3
- Nature Chemistry 2016, 8, 393-8

IOCD

- Underpins many other sciences
  - (e.g. physical, bio- & nano-) that depend on understanding matter at molecular levels
- Requires seeing beyond the trees – looking at the *whole forest* AND the *environment* in which it is situated:
  - chemistry as a system coherently organised to understand & explain behaviour and transformations

    → Value in teaching chemistry: interest through understanding beyond rote learning
  - looking at how chemistry interacts dynamically with other systems to increase understanding, provide useful applications and help tackle global challenges

    → Value in relating chemistry to real-world problems, their origins and solutions

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
inventing itself or projecting
ary advances on prominent
orms, (2) it is intrinsically

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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, Mehta, Hopf & Krief
- Nature Chemistry 2015, 7, 941-3
- **Nature Chemistry 2016, 8, 393-8**

I O C D

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

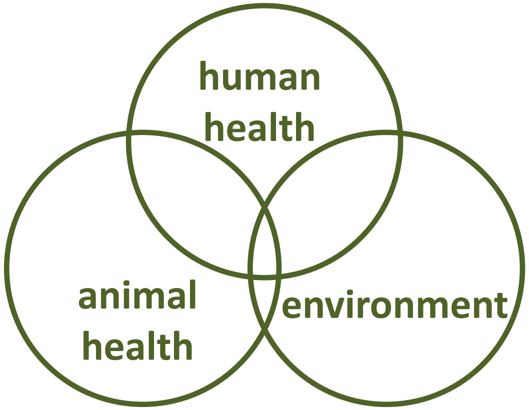
'One-world chemistry'

Aims to be:

- A science for the benefit of society
  - Ethical practice
  - Systems thinking (ST)
  - 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 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

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 Century

- *"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 and partly quantified

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

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

____

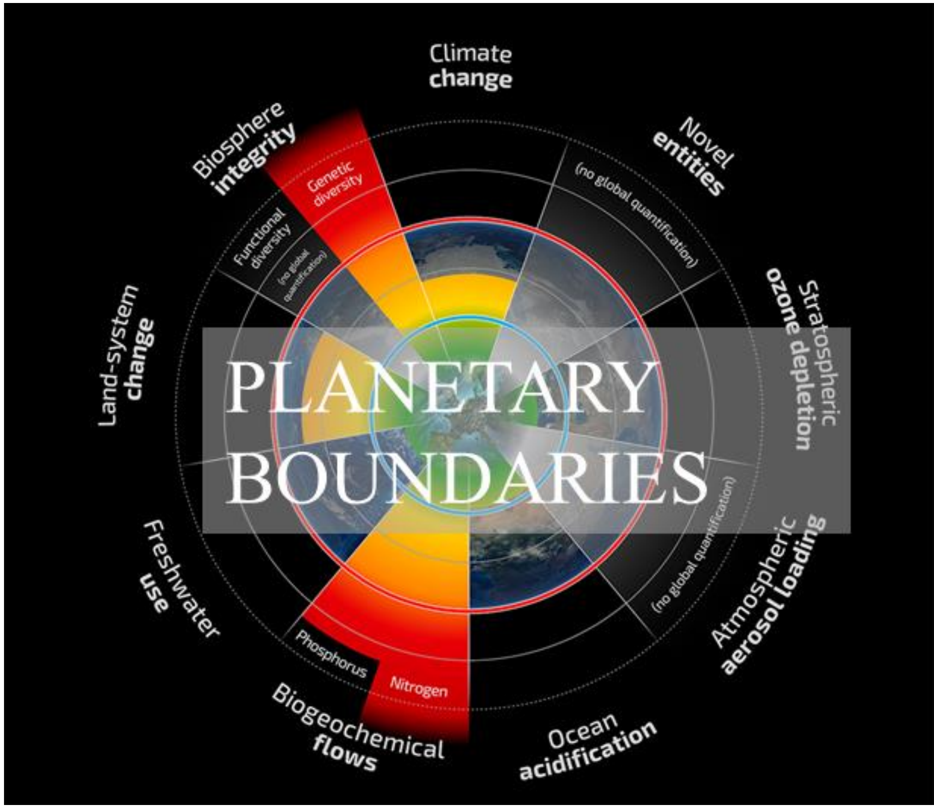
"…leaving no-one behind"

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

9 Planetary boundaries

Nine Earth system processes which have boundaries proposed in 2009 by a group of Earth system and environmental scientists led by Johan Rockström from the Stockholm Resilience Centre and Will Steffen from the Australian National University.
…defining a "safe operating space for humanity“

1. Climate change: atmospheric CO2, radiative forcing
2. Rate of biodiversity loss
3. Biogeochemical cycles: N, P
4. Stratospheric ozone depletion
5. Ocean acidification
6. Atmospheric aerosol loading
7. Global freshwater use
8. Change in land use: converted to cropland
9. Novel entities in environment: chemical pollution



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

Applying ST in chemistry

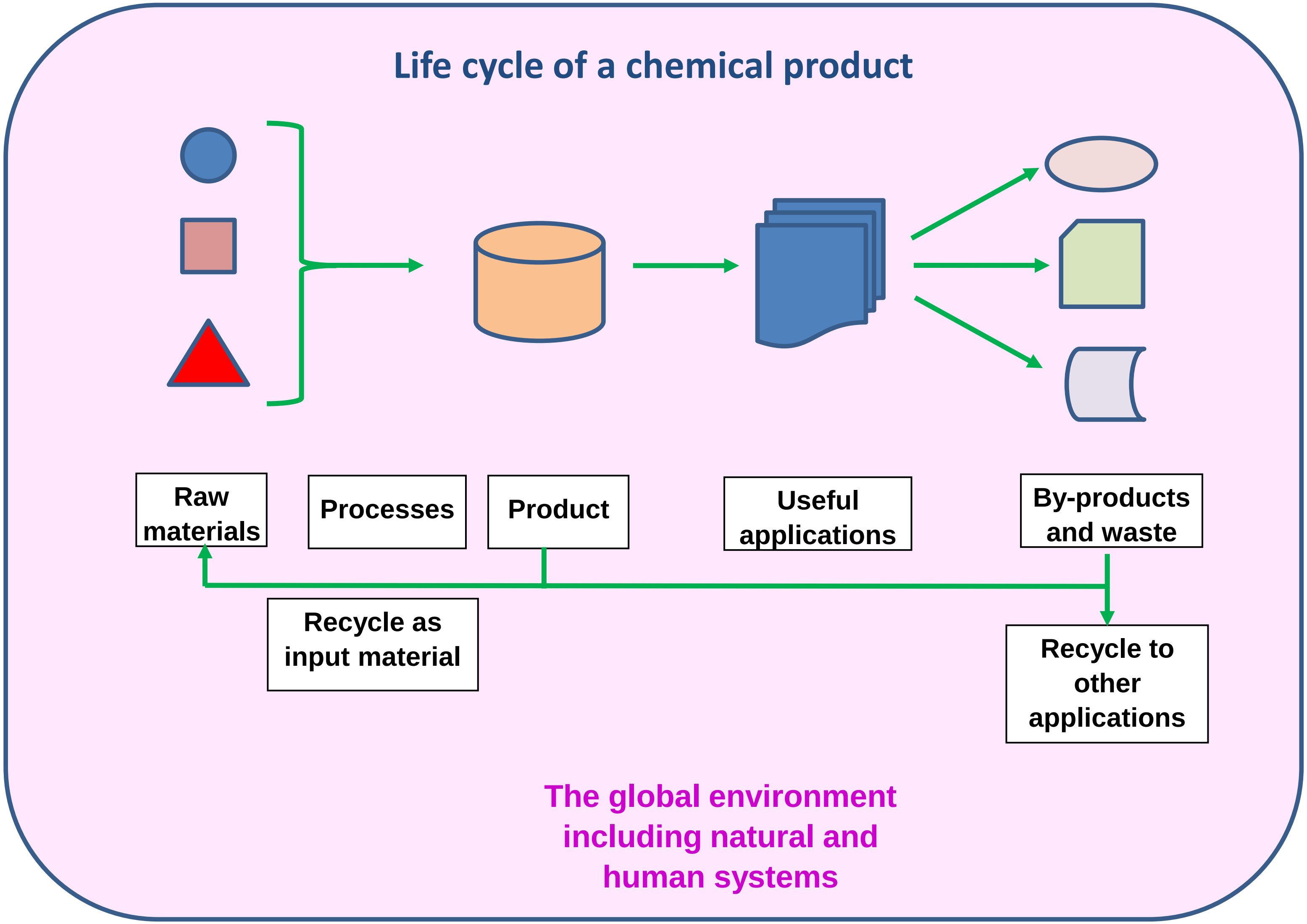
Elements of ST are found in these approaches

- Life Cycle Analysis
- Green Chemistry
- Molecular Basis of Sustainability

Applying ST in chemistry

Elements of ST are found in these approaches

- Life Cycle Analysis



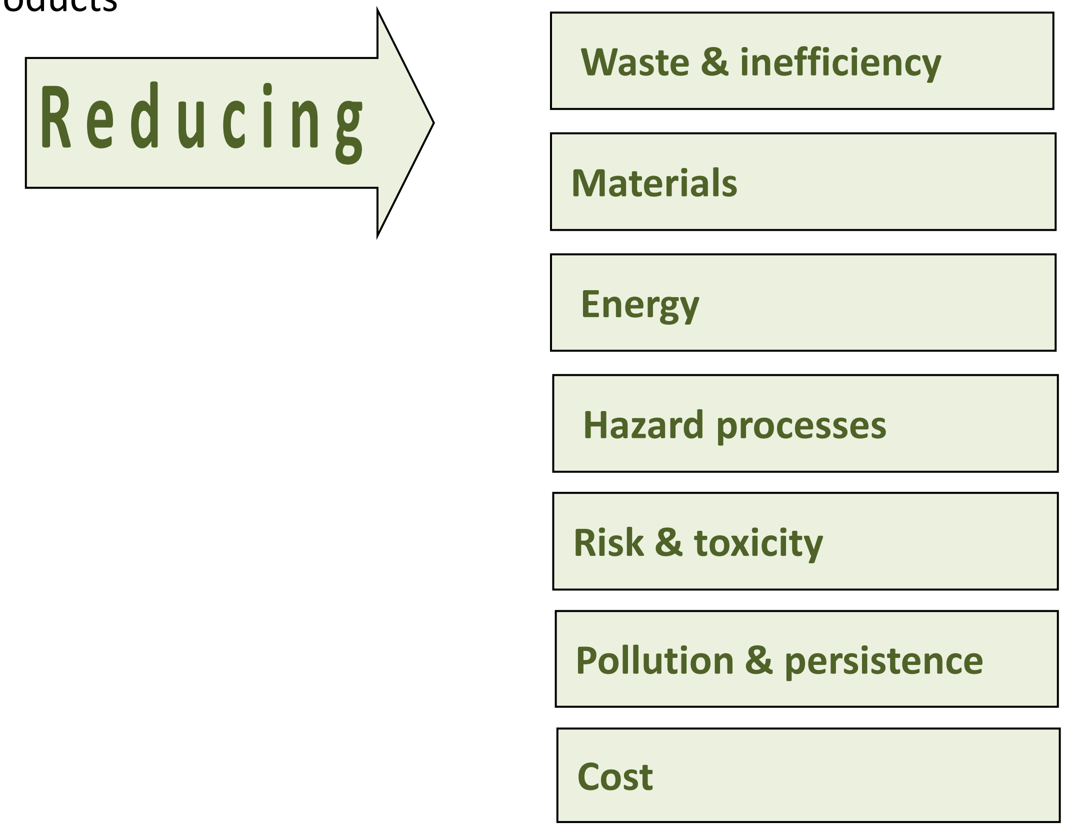
Applying ST in chemistry

Elements of ST are found in these approaches

- Life Cycle Analysis
- Green Chemistry

12 Green Chemistry Principles

reducing or eliminating the use or generation of hazardous substances in the design, manufacture and application of chemical products



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

Review: Green Chemistry 2018, DOI: 10.1039/c8gc00482j

Applying ST in chemistry

Elements of ST are found in these approaches

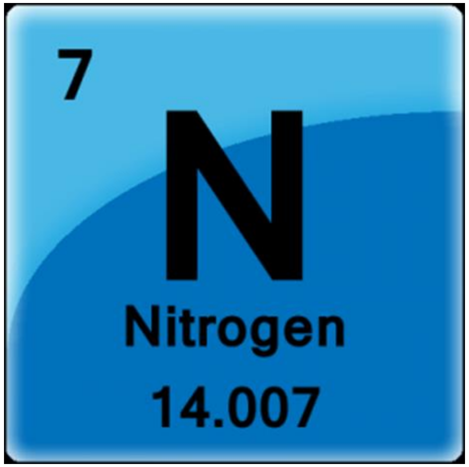
- Life Cycle Analysis
- Green Chemistry
- Molecular Basis of Sustainability

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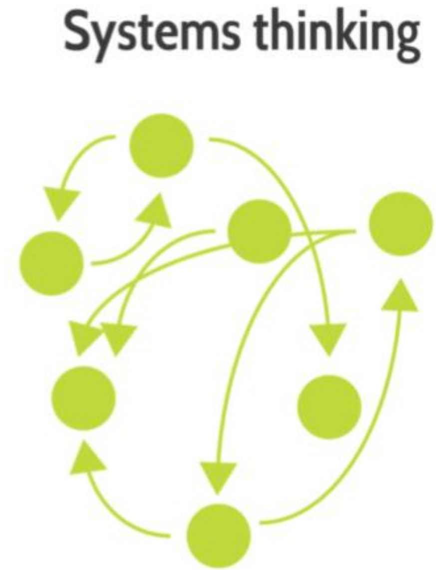
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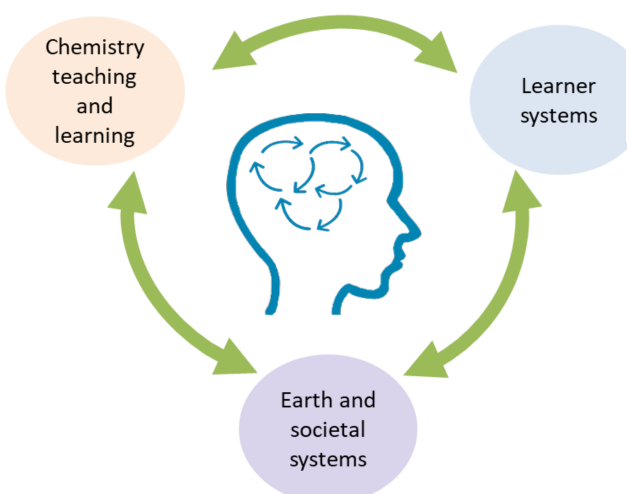
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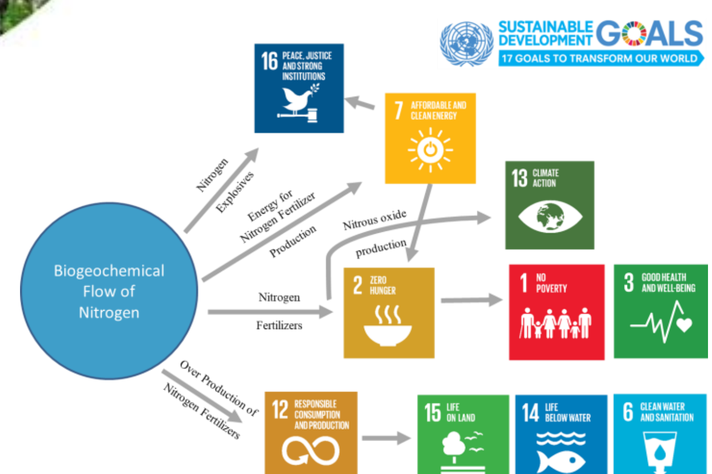
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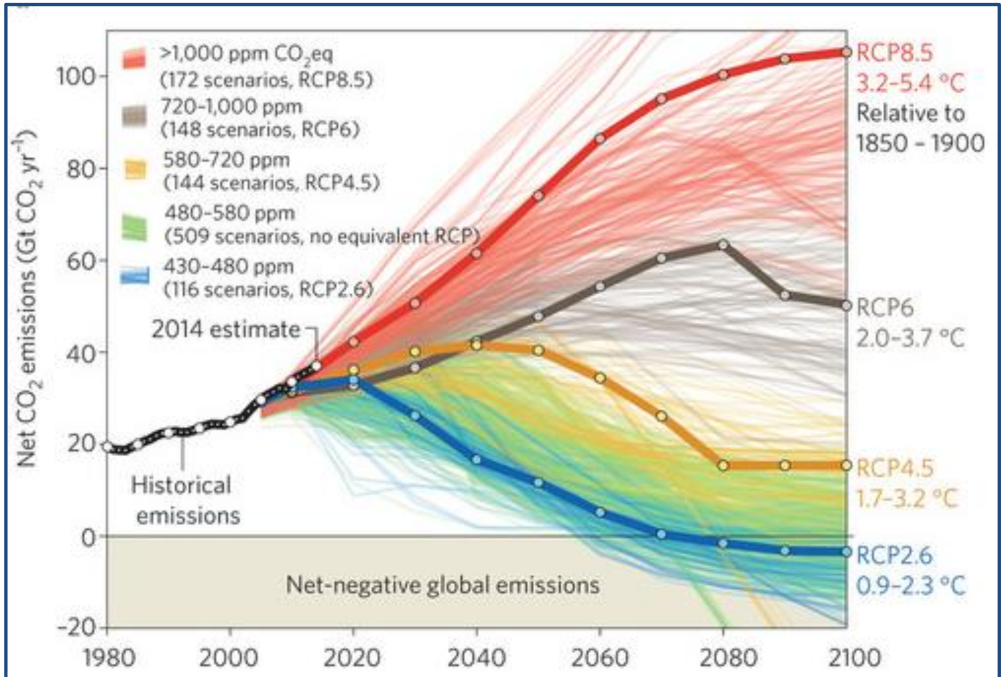
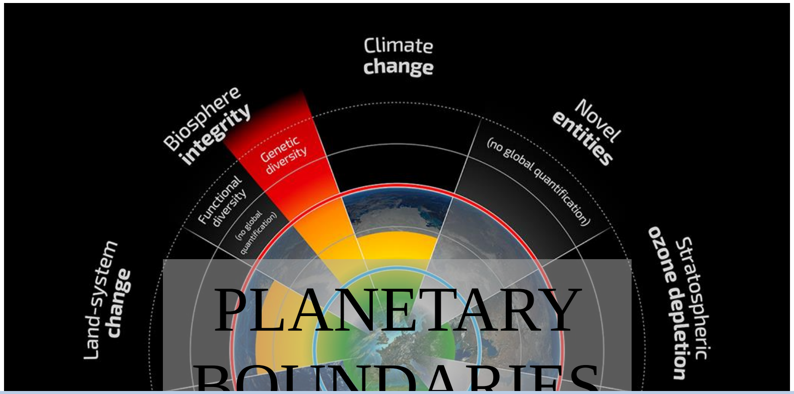
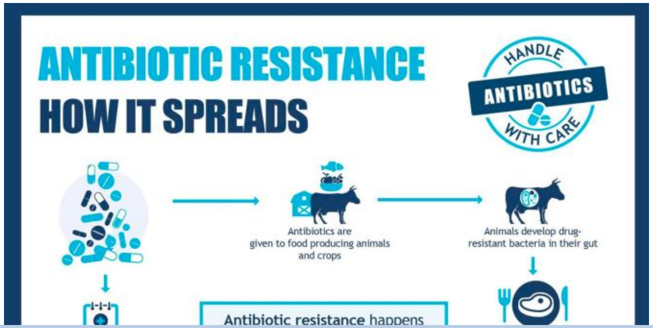


Nature Climate Change 4, 850–853 (2014)





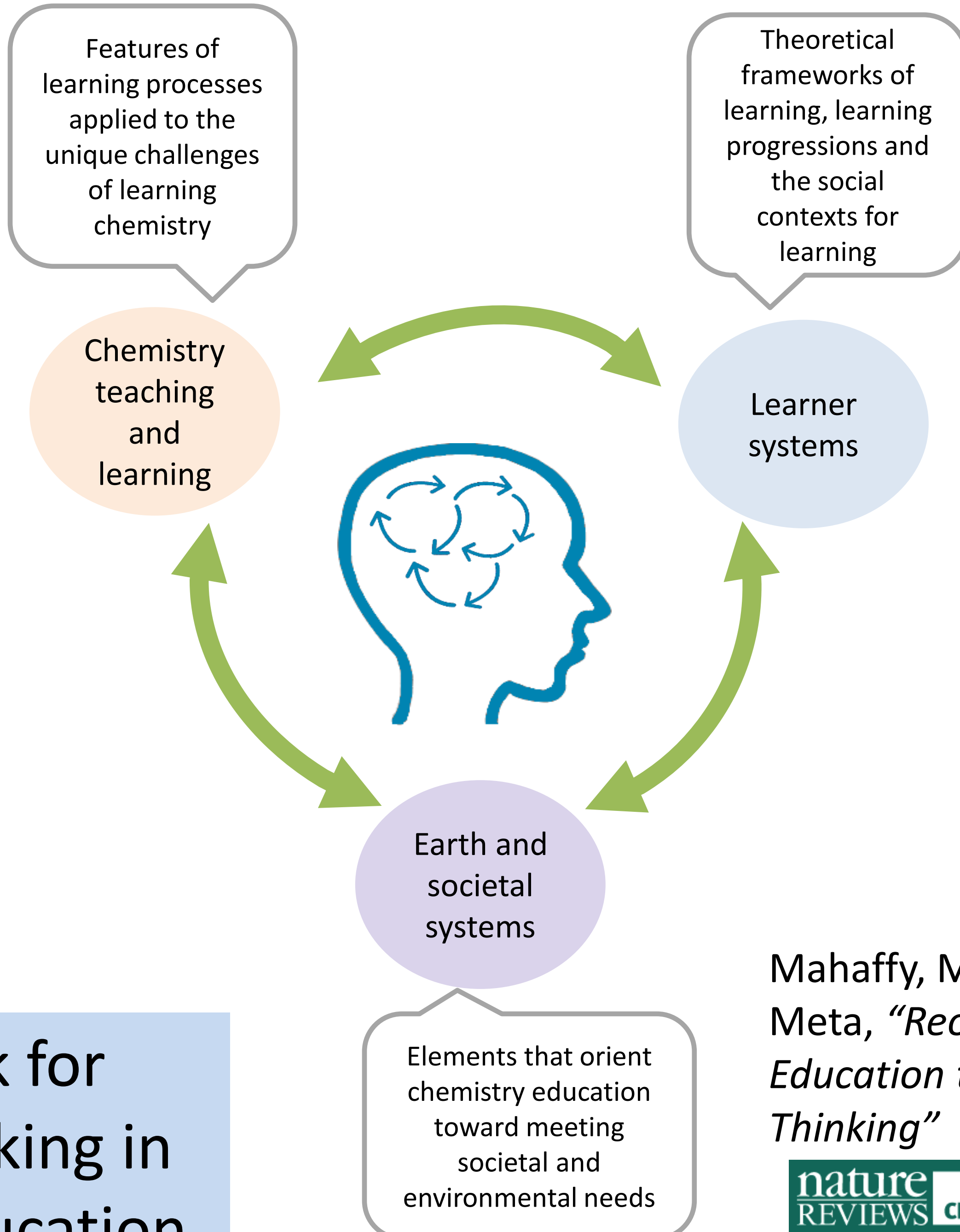
Do students leave gateway science courses knowing how their knowledge helps to understand and meet multiple emerging global challenges?

Learning Objectives and Strategies for Infusing Systems Thinking into (Post)-Secondary General Chemistry Education

IUPAC
International Union of Pure and Applied Chemistry

IUPAC Project # 2017-010-1-050

- Help students move from fragmented knowledge of chemical reactions and processes to a more holistic view, equipping them to better address emerging global challenges through chemistry education
- Develop learning objectives, and perhaps a tool kit, to help educators infuse systems thinking into (general) chemistry courses
- Identify barriers and develop strategies to guide the use of learning objectives based on ST in the design of curriculum and selection of engaging pedagogies
- Disseminate outcomes for both the chemistry education and broader science communities



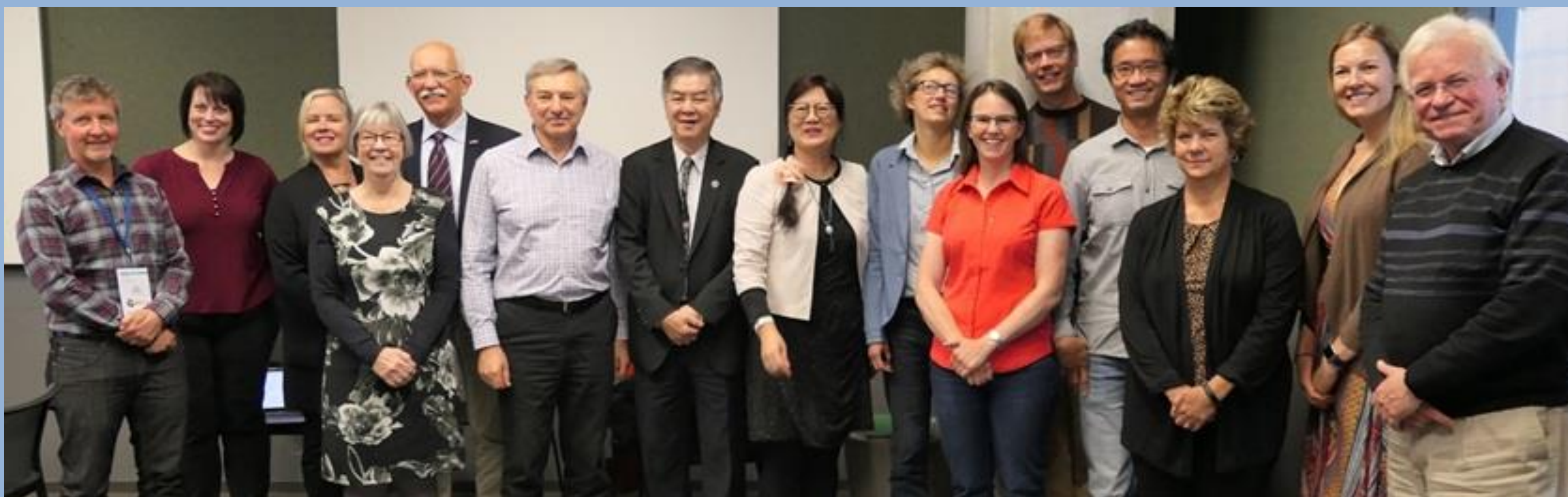
Framework for Systems Thinking in Chemistry Education

Mahaffy, Matlin, Krief, Hopf, Meta, *"Reorienting Chemistry Education through Systems Thinking"*

nature REVIEWS CHEMISTRY

(2018) VOLUME 2 | ARTICLE NUMBER 0126 | **1**

STICE Project Progress to Date

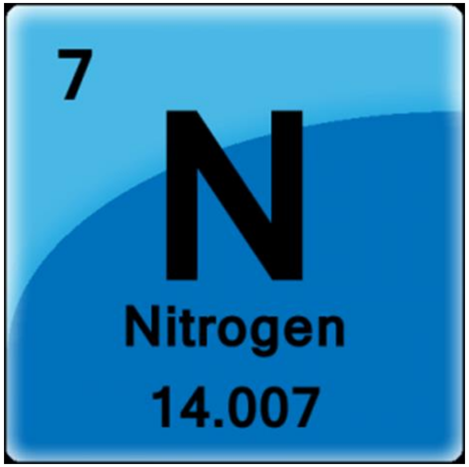


- ICCE and CONASTA 2018 Conference (Sydney) – workshop, symposium, project meeting

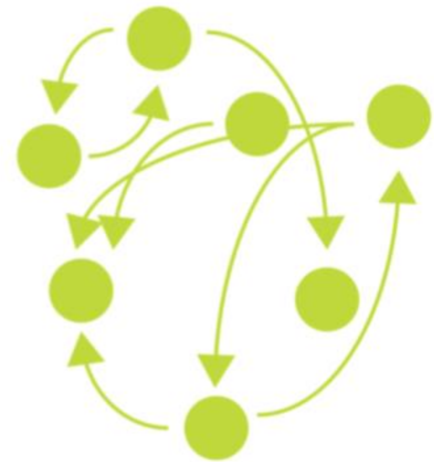
IUPAC Centenary - 2019

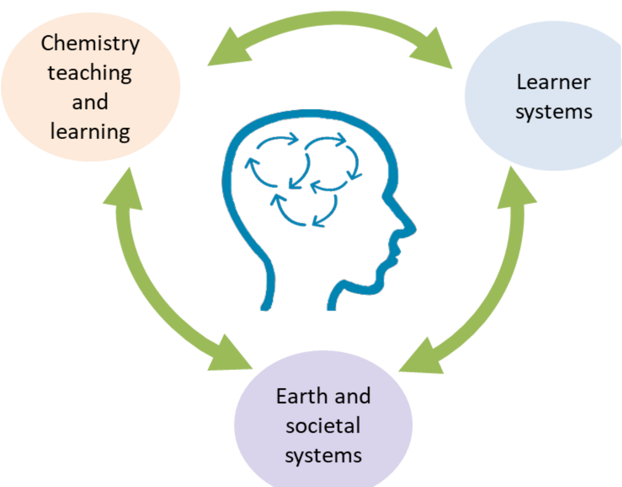
5 JULY 2019 - 12 JULY 2019

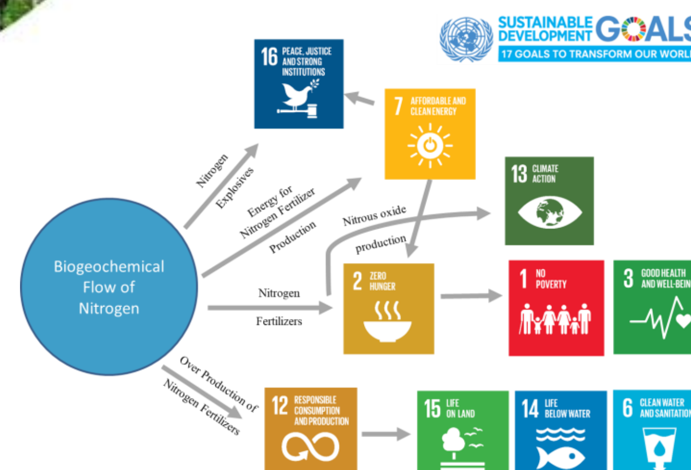
IUPAC 2019 PARIS FRANCE

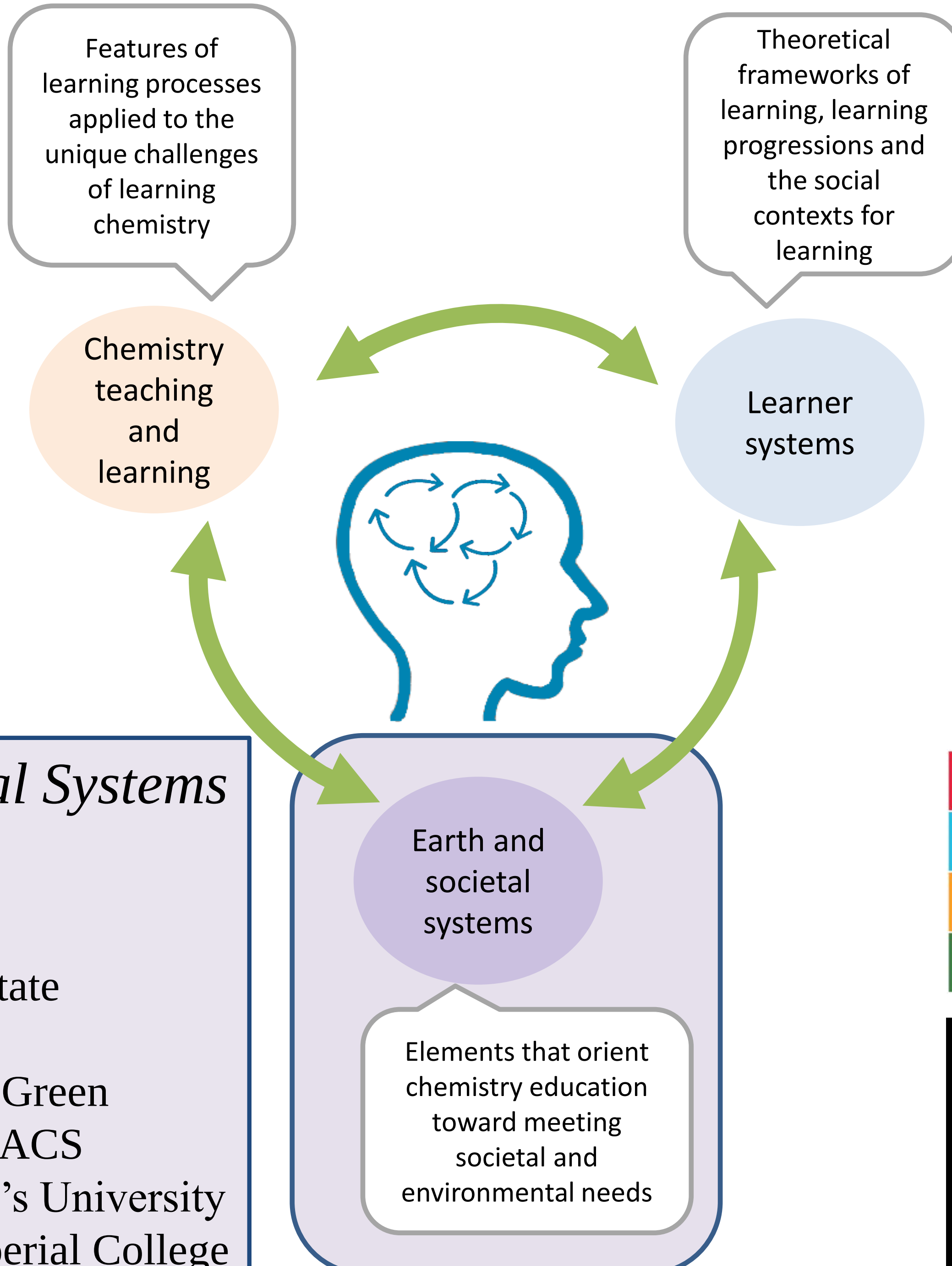


Systems thinking



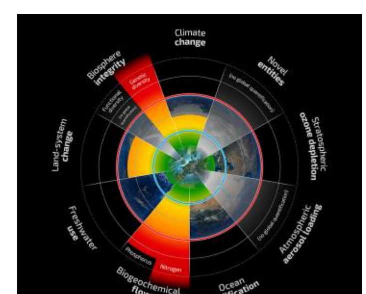






Earth and Societal Systems Node

- Tom Holme, Iowa State University
- Jennifer MacKellar, Green Chemistry Institute, ACS
- Peter Mahaffy, King's University
- Stephen Matlin, Imperial College



Education about Molecular Basis of Sustainability

The material basis of society is a core element in addressing sustainability challenges.

→

Practice chemistry with more consideration for the molecular basis of sustainability.

↓

Reorient chemistry education to address the sustainability of earth and societal systems

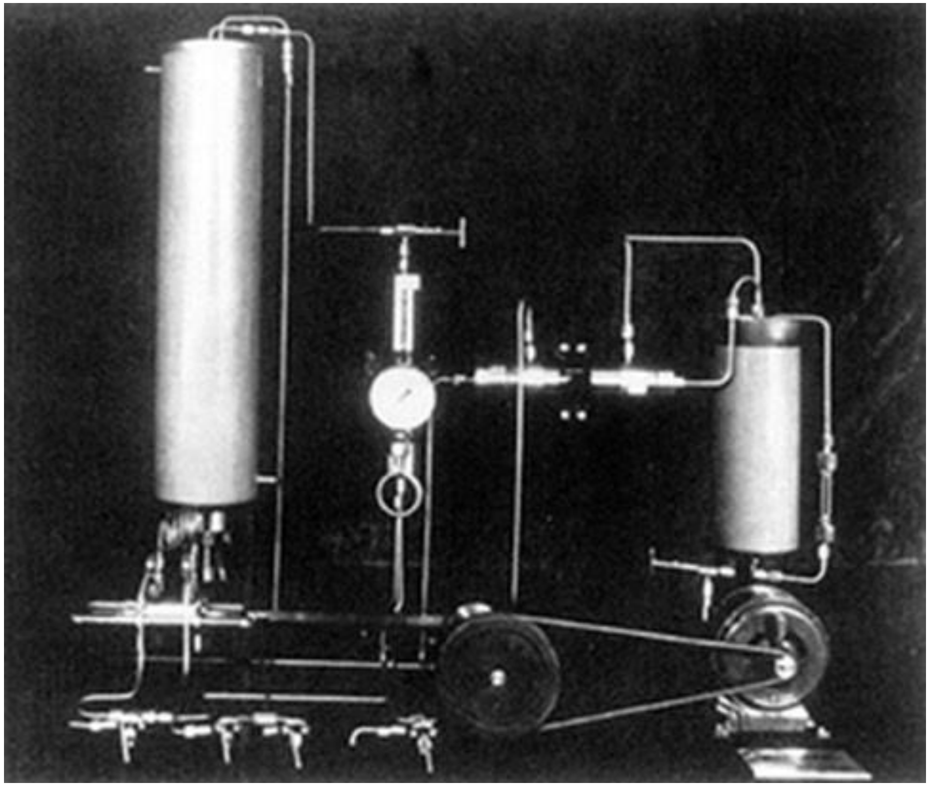
←

A systems thinking framework to connect education about the molecular world to the sustainability of earth and societal systems.

Earth and societal systems

The most important technological invention of the 20th Century?

The most important technological invention of the 20th Century?



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

Haber-Bosch Process

The most important technological invention of the 20th Century?

"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."

Vaclav Smil

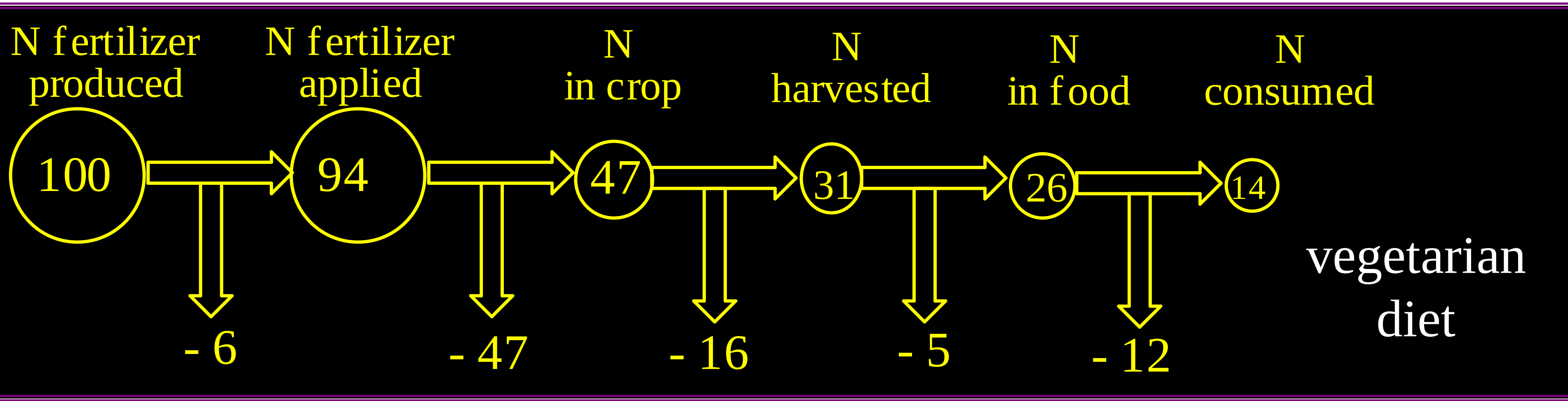
University of Manitoba

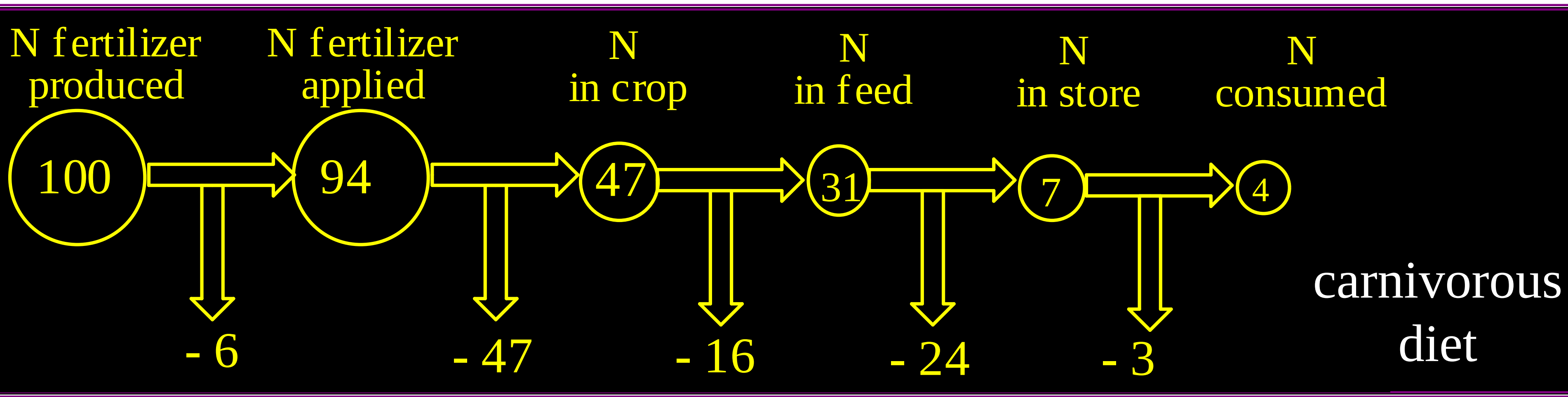
$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$$

V Smil, Nature 1999, 400, 415

Yet, a Failure of Systems Thinking in Chem?

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





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

And a Failure of Systems Thinking in Chem Ed?

- Texts show ammonia synthesis in equilibrium chapter, often with a (sanitized) sidebar on Haber, Nobel laureate
- Classroom treatment and assessment focuses on mathematical calculations related to changing concentrations and pressures (ICE tables?)
- No connection usually made between this chemical reaction and either the survival of 40% of our planet's human beings or the threat to our planetary boundaries of our massive fixed nitrogen footprint.

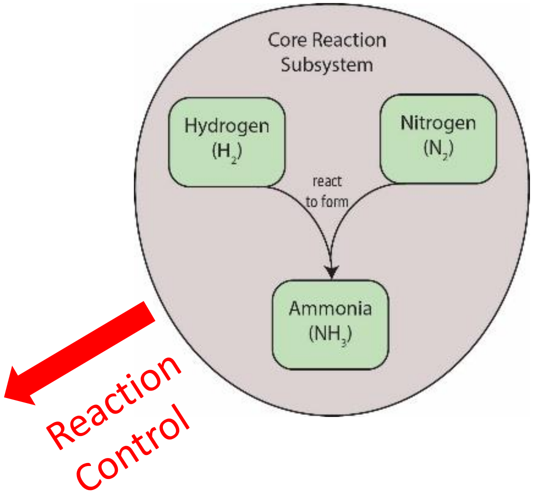
Fritz Haber was a German chemist who received the Nobel Prize in Chemistry in 1918 for his invention of the Haber-Bosch process, the method used in industry to synthesize ammonia from nitrogen and hydrogen gases.

Applying STICE Framework to N and its Compounds

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

Building a systemigram:
Choosing the system boundaries to extend the picture to the level desired

(Prof. Tom Holme talk)



Building a systemigram: Choosing the system boundaries to extend the picture to the level desired

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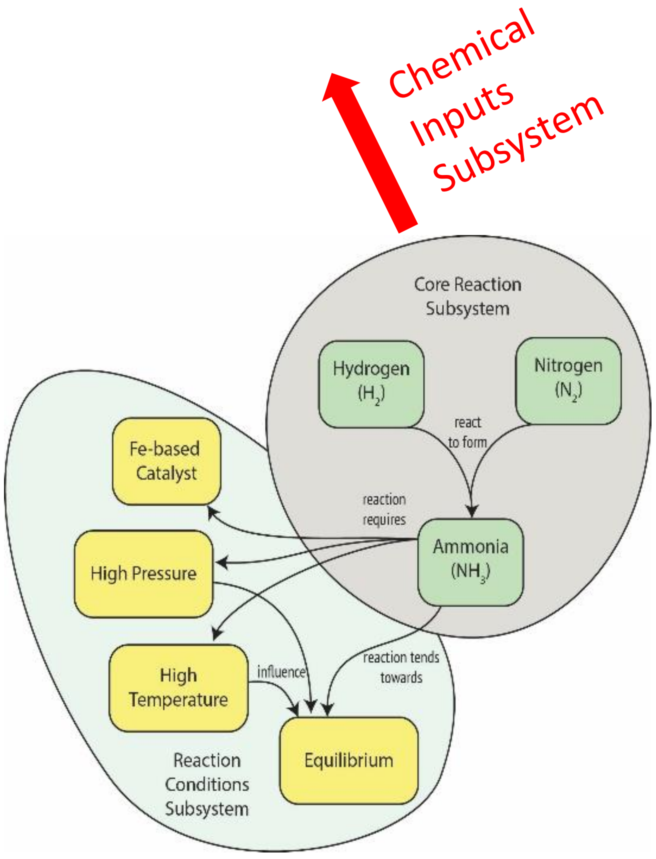

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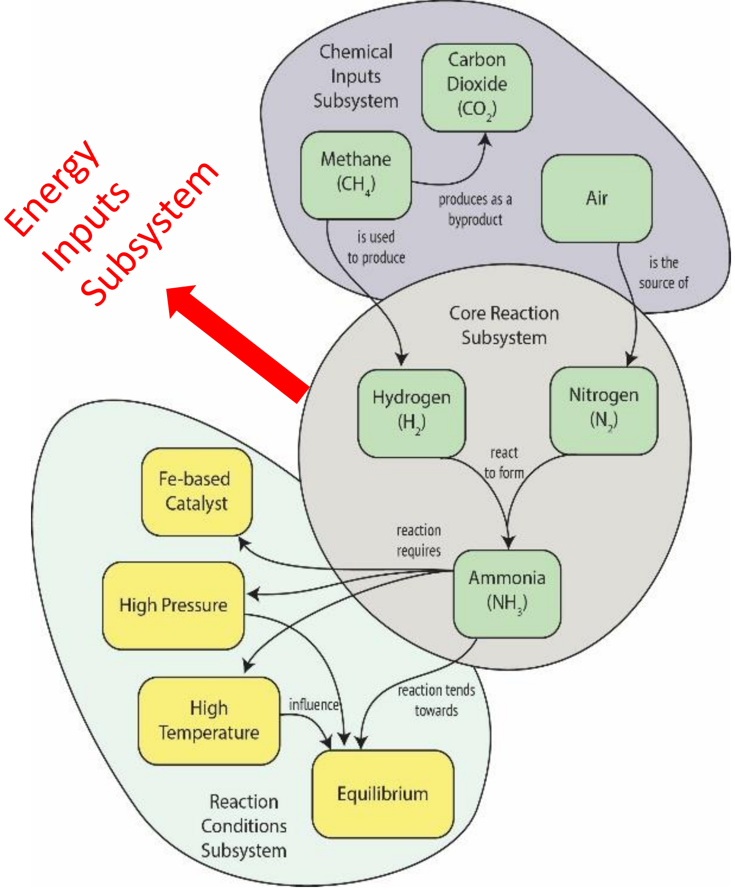

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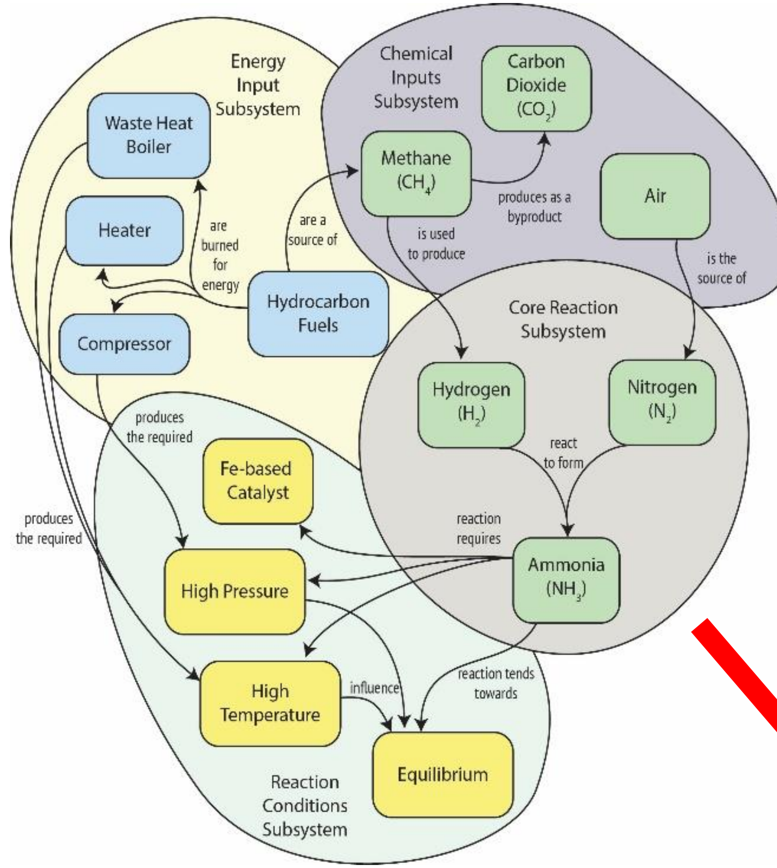
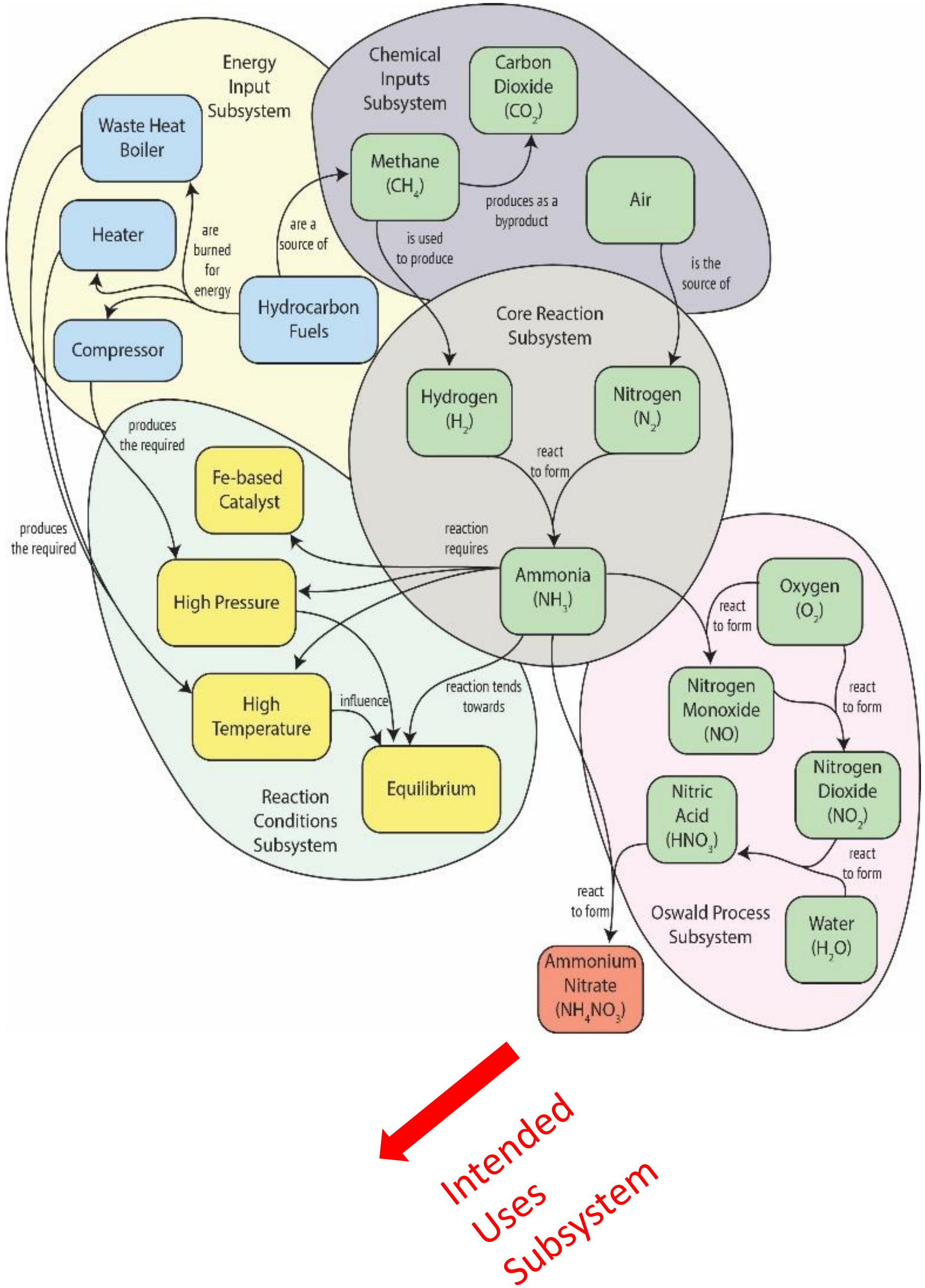


Oswald Process (HNO_3) Subsystem

Building a systemigram: Choosing the system boundaries to extend the picture to the level desired

(Prof. Tom Holme talk)



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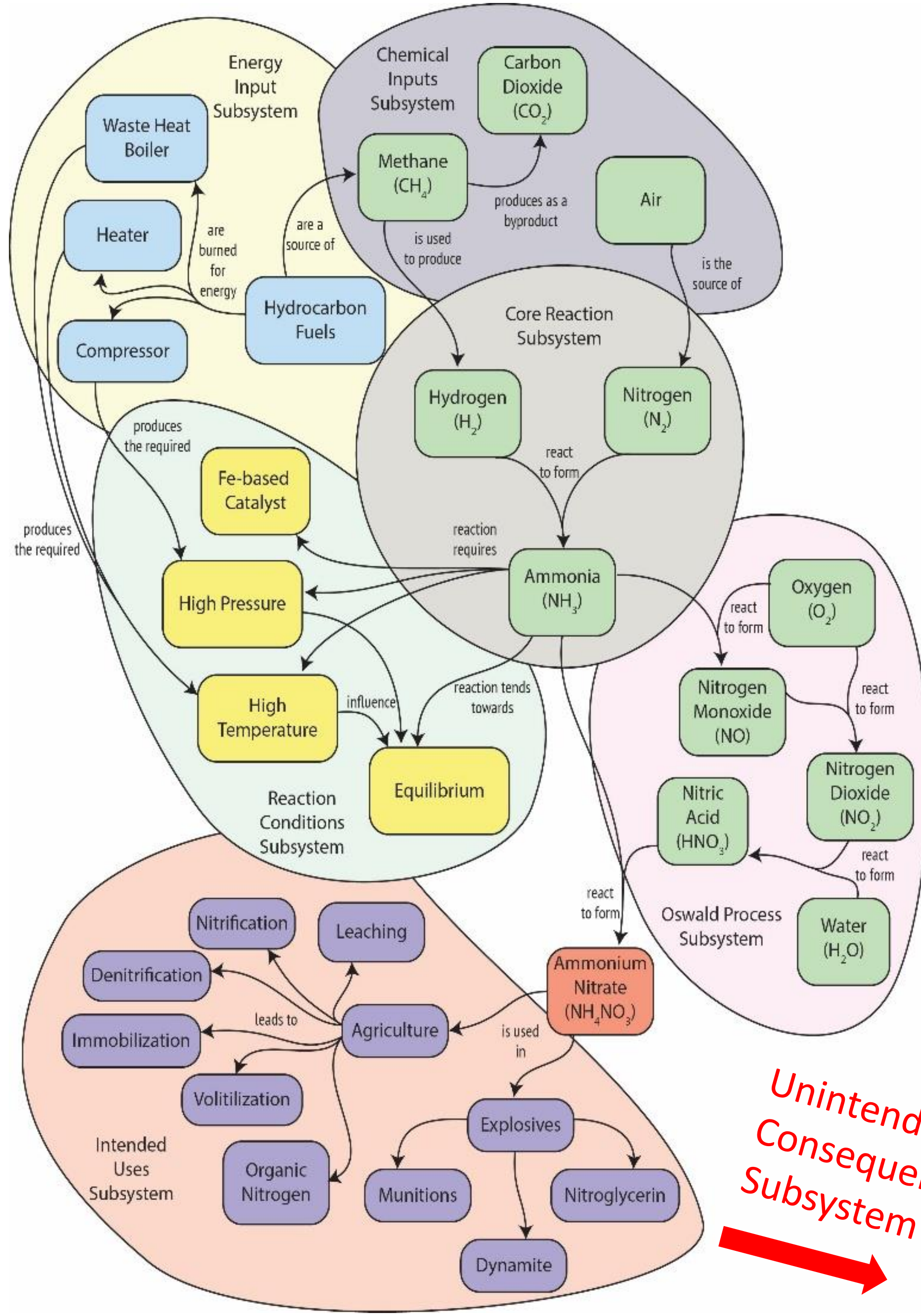
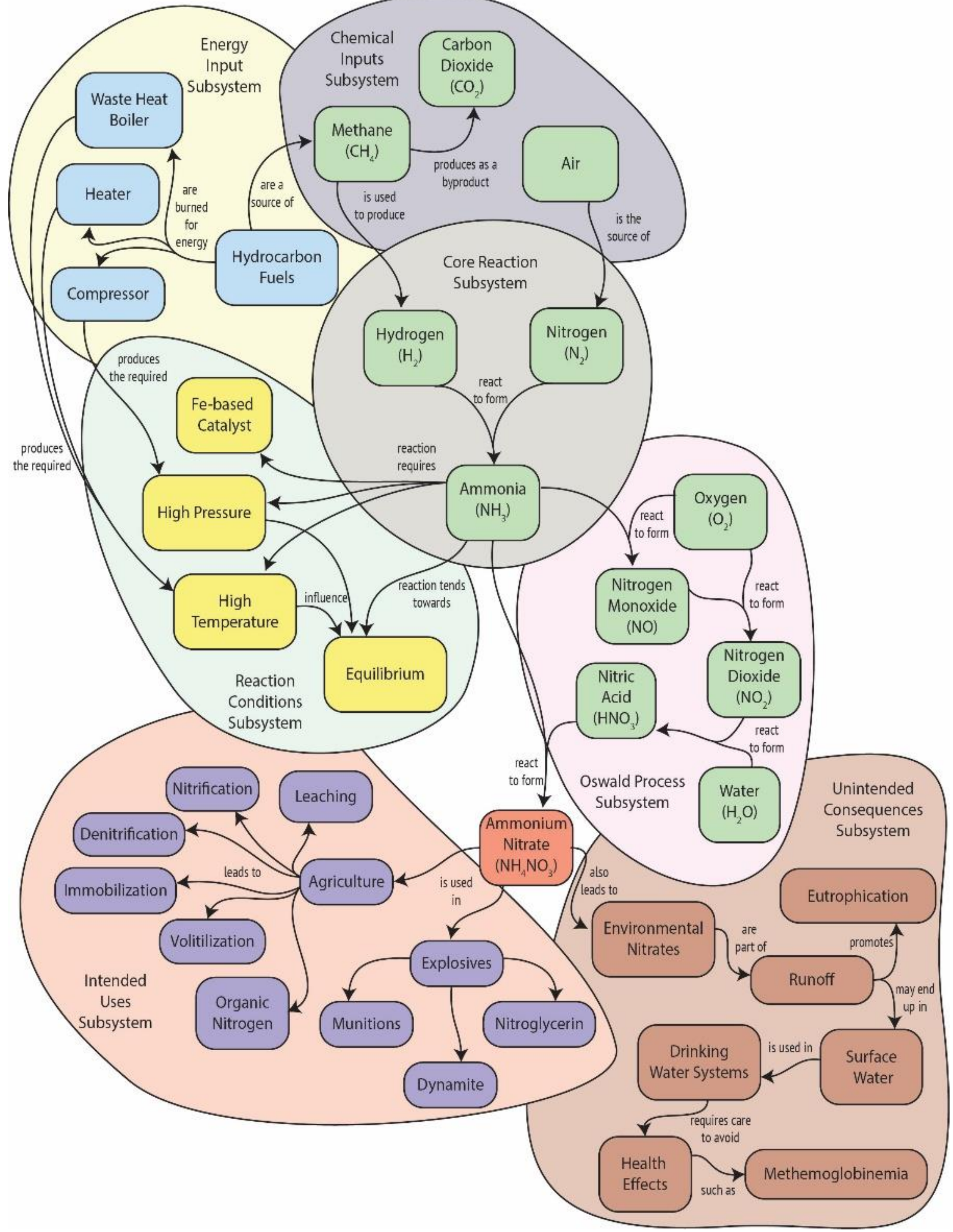
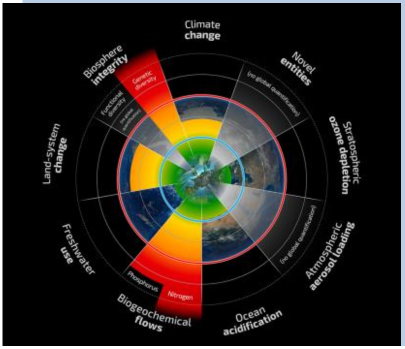


Unintended Consequences Subsystem

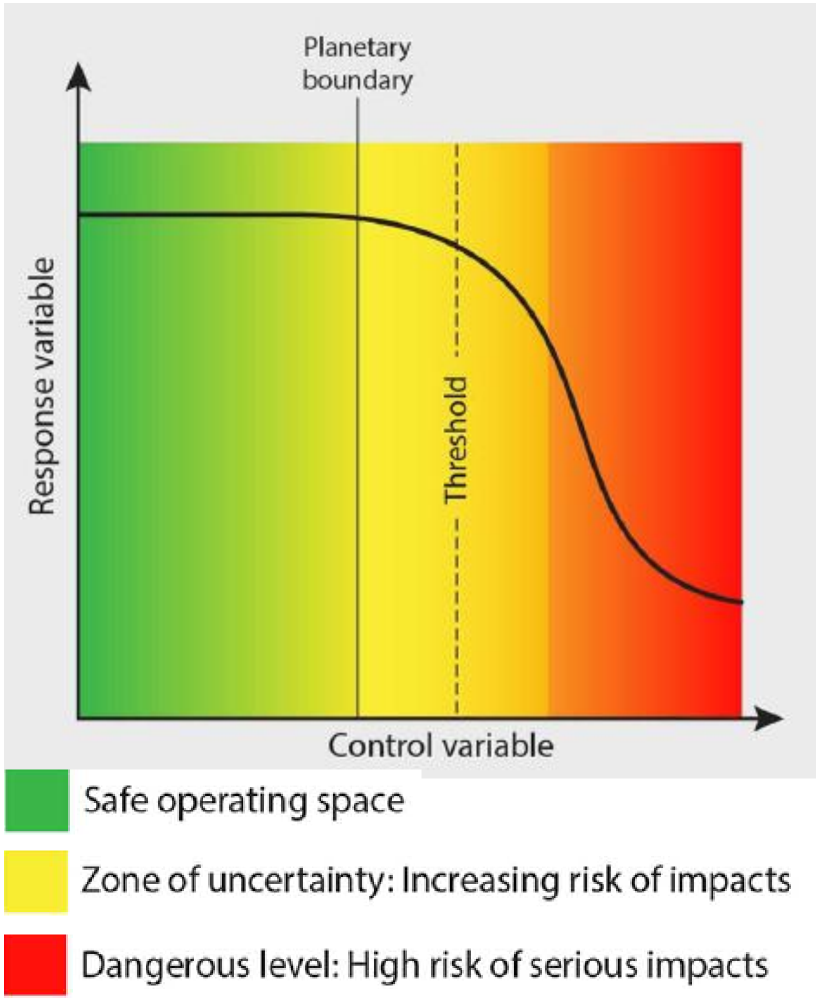
Building a systemigram: Choosing the system boundaries to extend the picture to the level desired

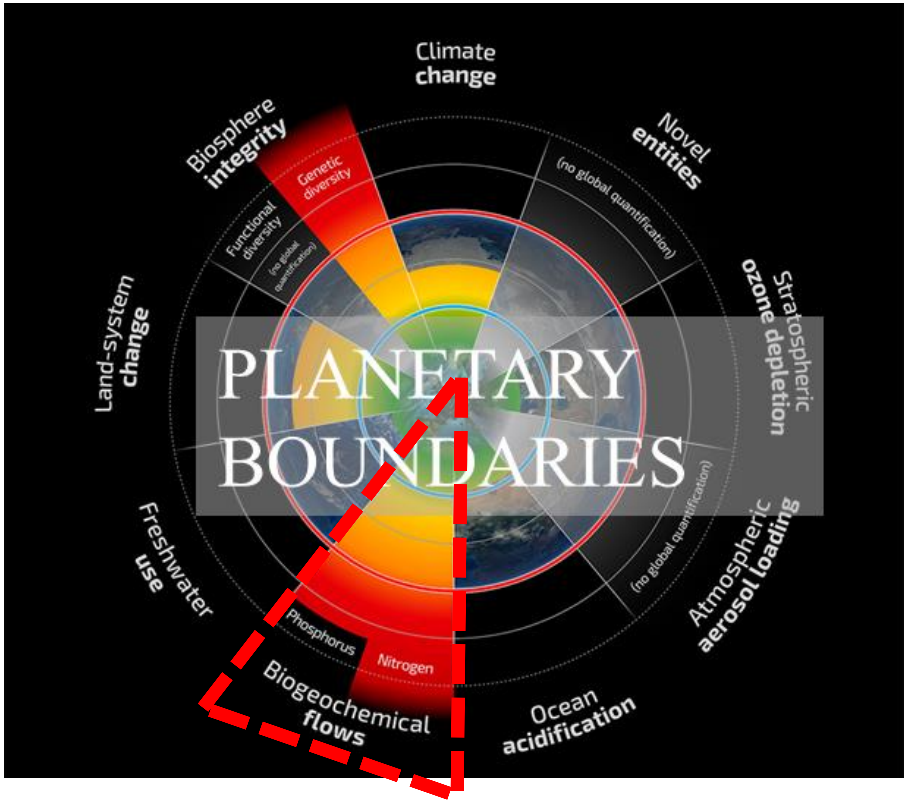
(Prof. Tom Holme talk)





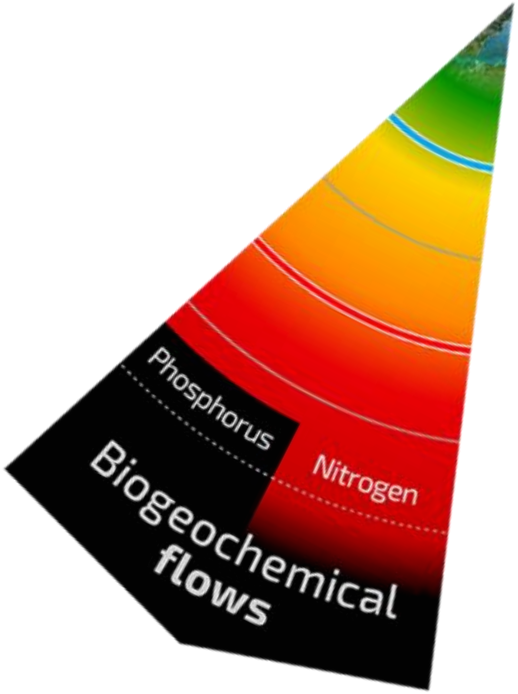
Planetary Boundaries & Thresholds



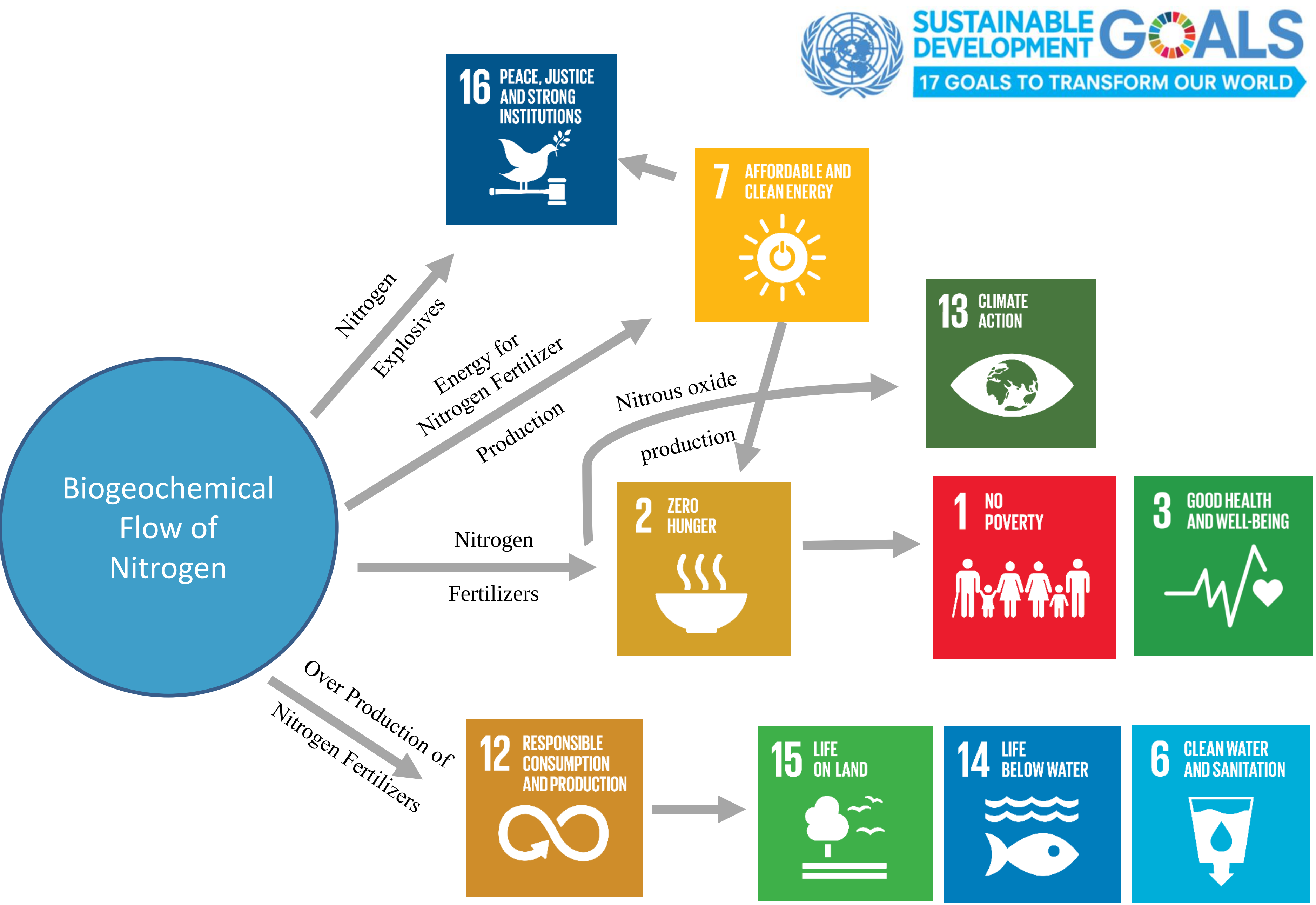


Johan Rockström, Will Steffen, et al.
Nature 2009, 461, 472-475
Science 2015, 347, Issue 6223, 1259855

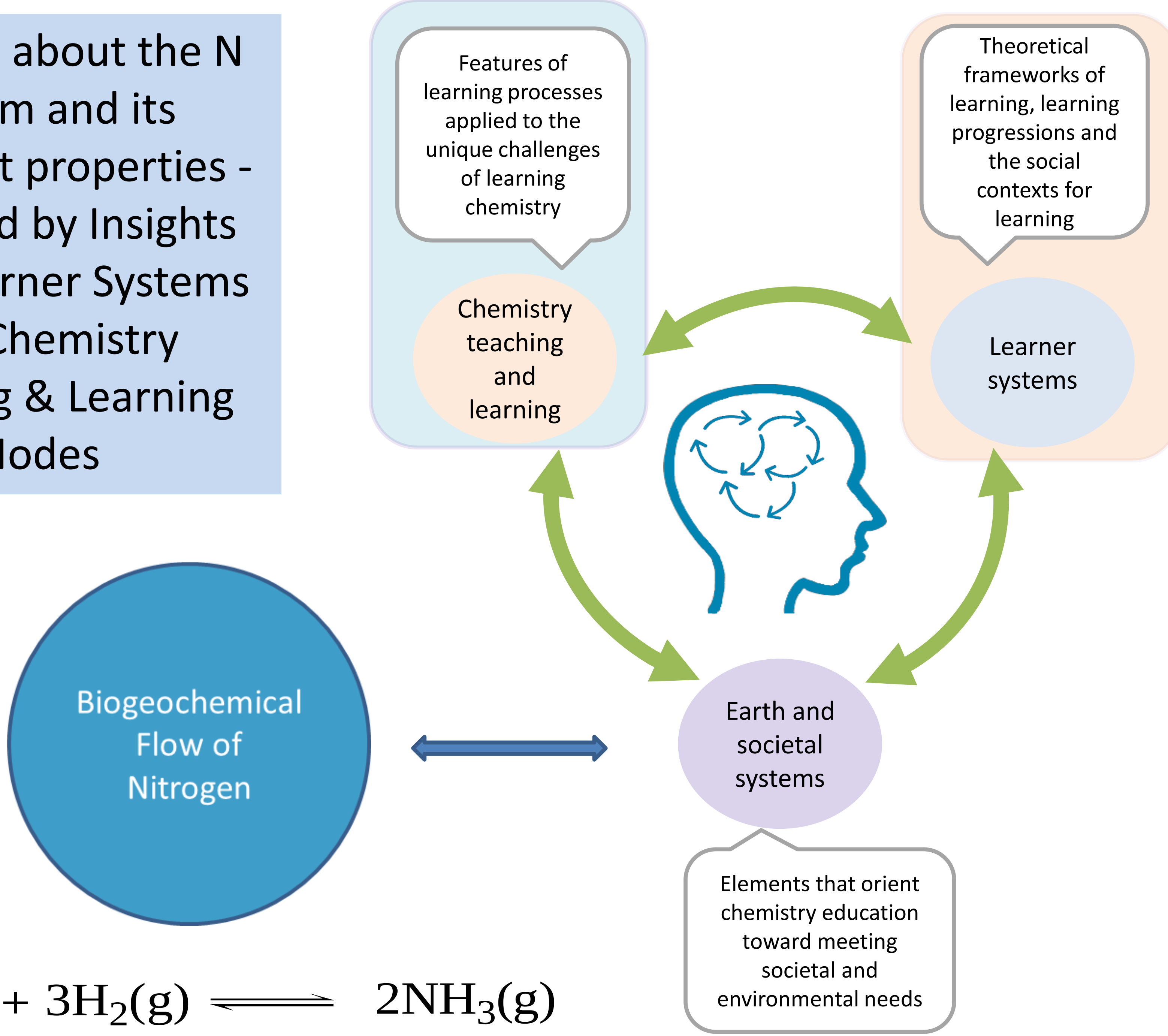
Nitrogen and its Compounds



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}


SUSTAINABLE DEVELOPMENT GOALS
17 GOALS TO TRANSFORM OUR WORLD
Biogeochemical Flow of Nitrogen
Nitrogen Explosives
Energy for Nitrogen Fertilizer Production
Nitrous oxide production
Nitrogen Fertilizers
Over Production of Nitrogen Fertilizers
16 PEACE, JUSTICE AND STRONG INSTITUTIONS
7 AFFORDABLE AND CLEAN ENERGY
13 CLIMATE ACTION
2 ZERO HUNGER
1 NO POVERTY
3 GOOD HEALTH AND WELL-BEING
12 RESPONSIBLE CONSUMPTION AND PRODUCTION
15 LIFE ON LAND
14 LIFE BELOW WATER
6 CLEAN WATER AND SANITATION

Learning about the N system and its emergent properties - Informed by Insights from Learner Systems and Chemistry Teaching & Learning Nodes

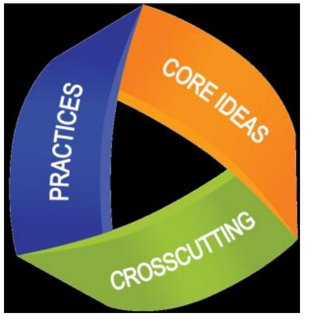


$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$$

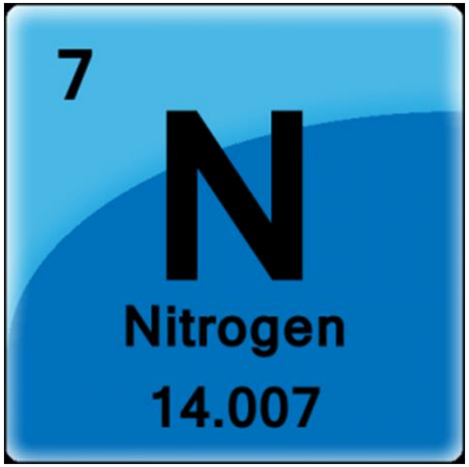
Learning Outcomes: Nitrogen and its Compounds

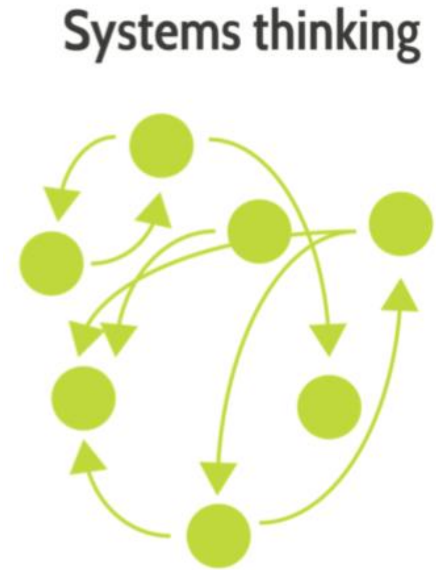
- What should the system boundaries be? What should students "know, do, and value"* at the end of my STEM coverage of nitrogen and its compounds?
- Do student STEM learning outcomes about nitrogen compounds reflect 3D learning (NGSS – Practices, Crosscutting Concepts, and Disciplinary Core Ideas).
- Do student STEM learning outcomes include a systems perspective on nitrogen compounds and their importance to the lives of students and to the planet (molecular basis of sustainability)?
- Can students clearly articulate their own learning outcomes and do they see them reflected in assessments?

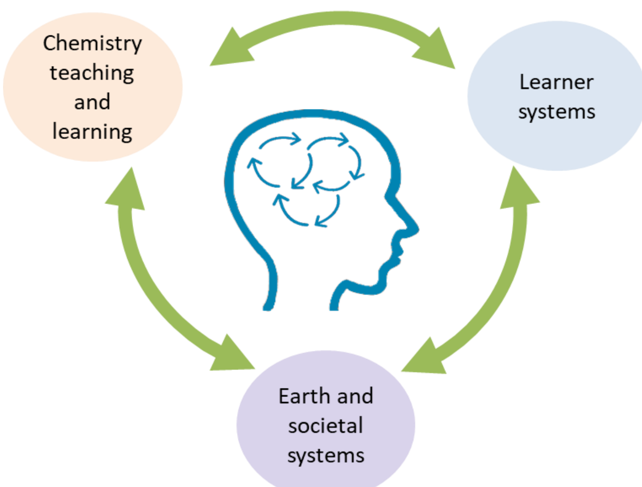
SUSTAINABLE DEVELOPMENT GOALS
17 GOALS TO TRANSFORM OUR WORLD



* Definition of student learning outcomes


7
N
Nitrogen
14.007


Systems thinking


Chemistry teaching and learning
Learner systems
Earth and societal systems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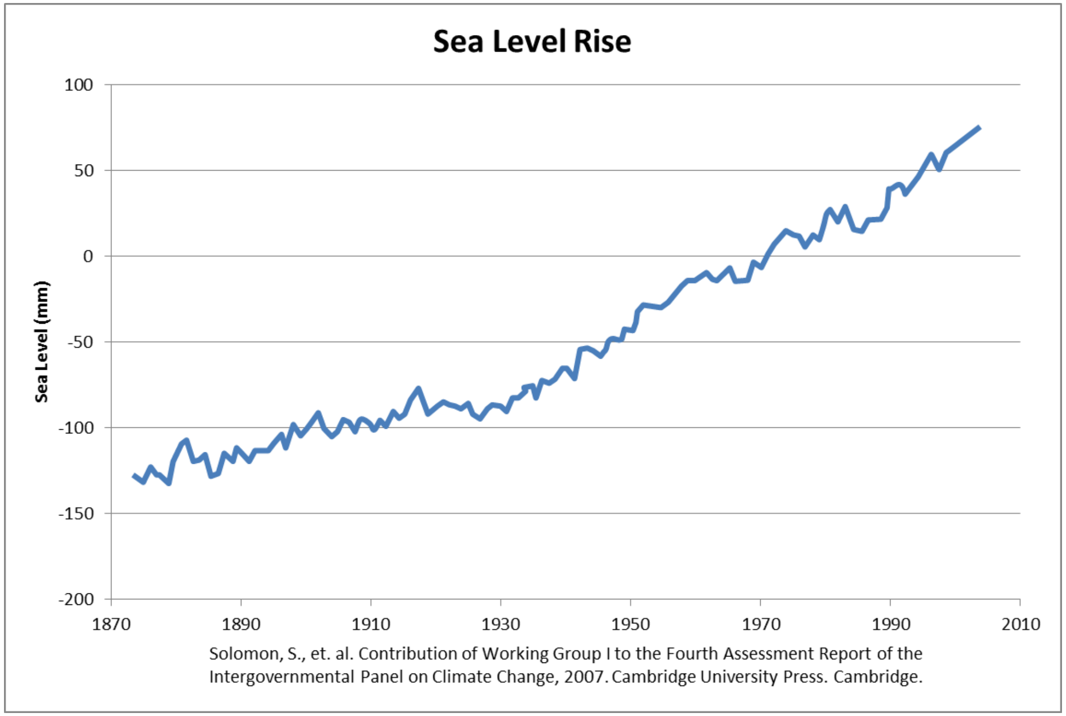
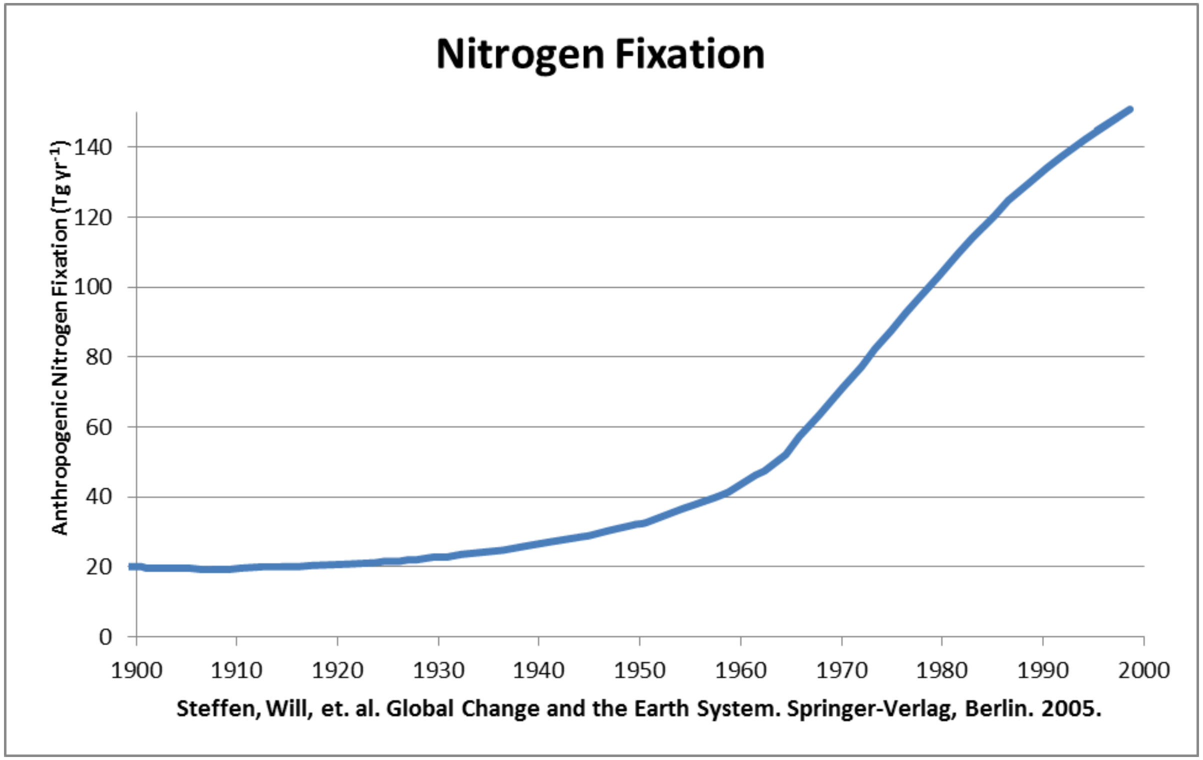
Kinetics of earth systems

IUGS
Earth Science for the Global Community

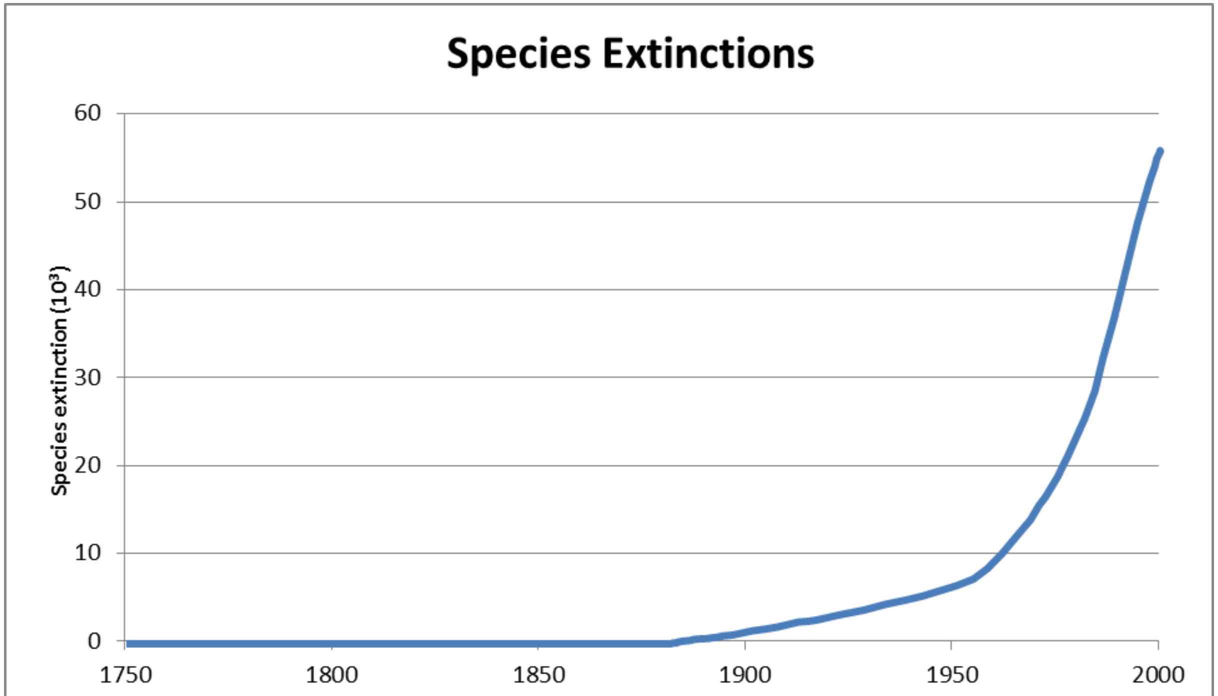
Kinetics of earth systems



Kinetics of earth systems

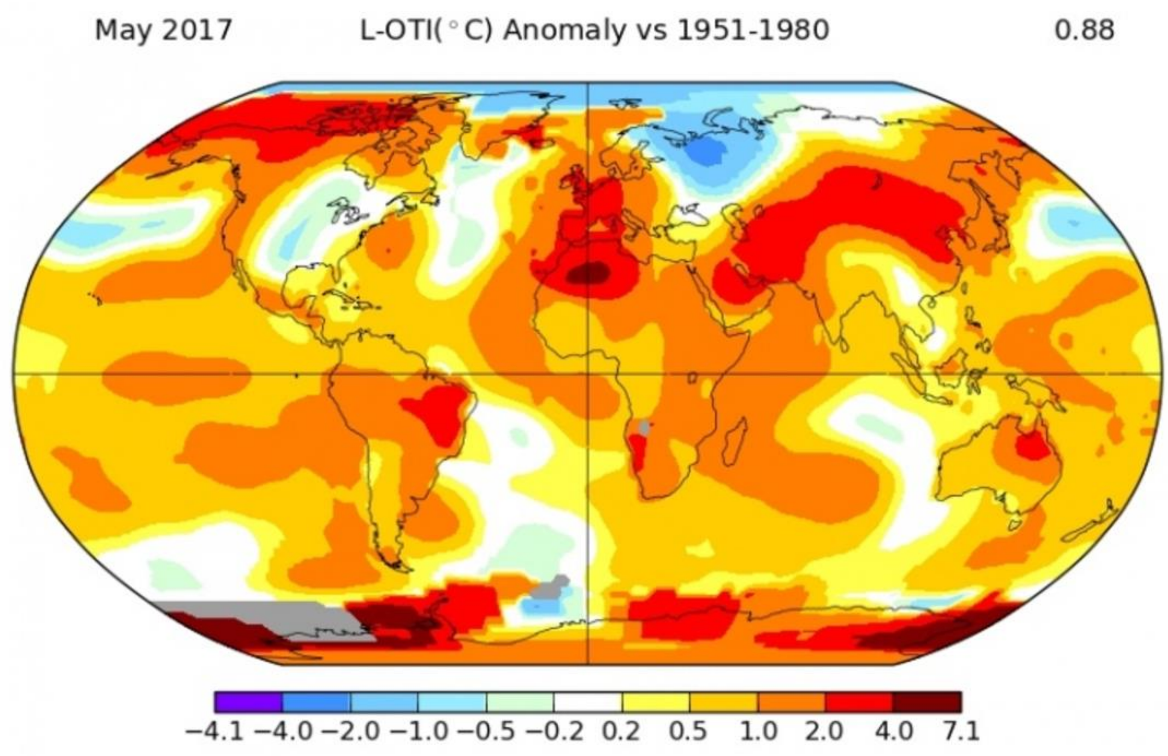


Kinetics of earth systems



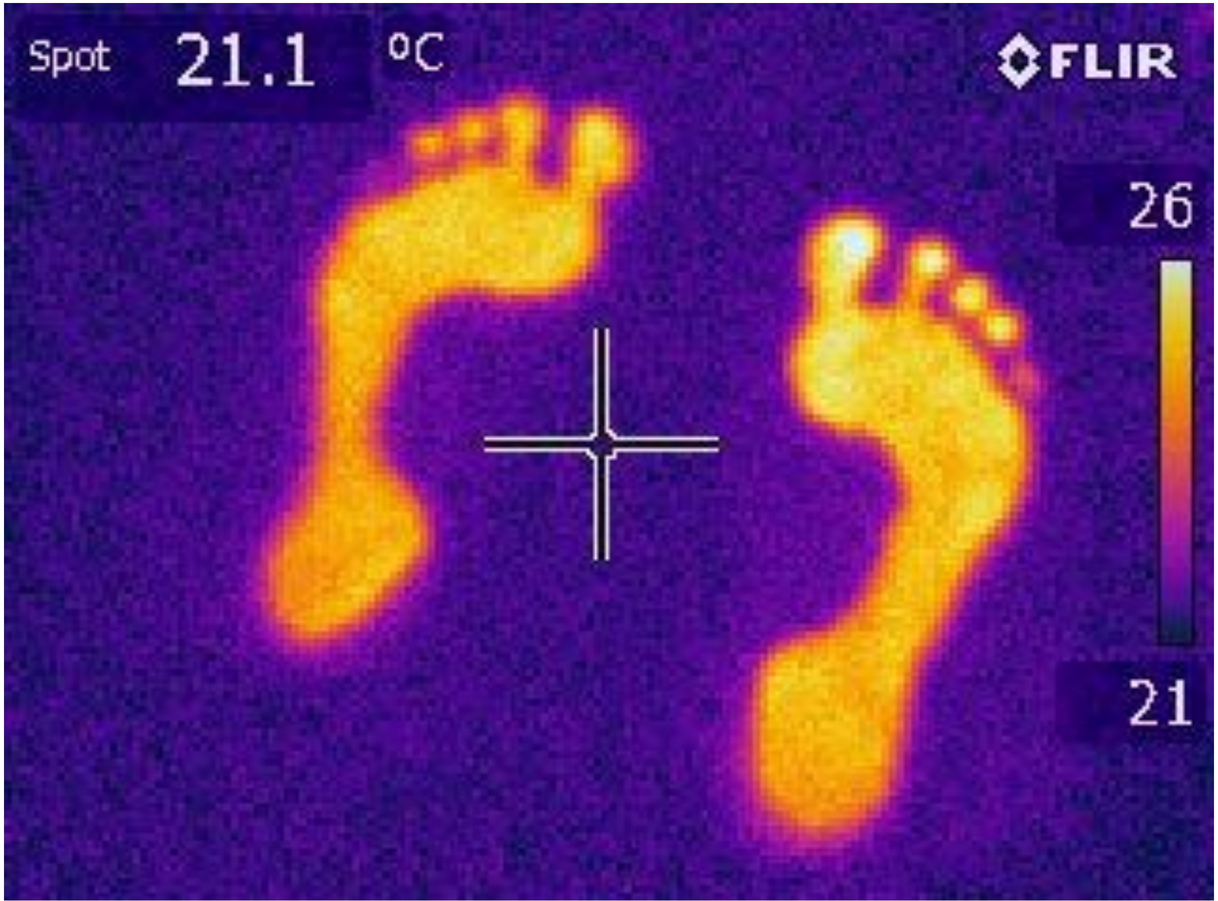
Steffen, Will, et. al. Global Change and the Earth System. Springer-Verlag, Berlin. 2005.

Kinetics of earth systems



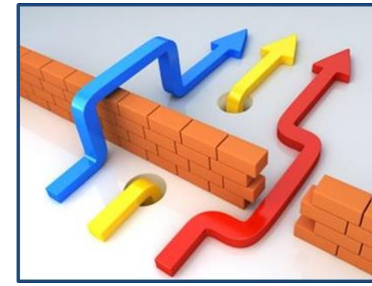
This May was the second-hottest May on record.
Credit: NASA GISS

Kinetics of earth systems



Kinetics of education systems

Systems thinking in chemistry education: Barriers to change



- Overcrowded curriculum
- Student expectations
- Student readiness for higher order learning tasks
- Potential for cognitive overload
- Faculty knowledge base
- Faculty inertia
- Developing appropriate assessments
- Accreditation standards

= Resistance to curriculum and pedagogy change!

You are already likely using ST strategies and tools

- Understand learners and learning needs!
- Help learners “pinch and zoom out” – to discover the forest while amidst the trees
- Learning from rich contexts
- Case-based learning
- Problem-based learning
- Tri-partite learning outcomes
- NGSS – 3D learning (core disciplinary concepts, cross-cutting concepts, and science practices)
- Chemical thinking learning progressions
- Life cycle analysis

Other STICE Talks/Workshops at ICCE

SYSTEMIGRAMS AS TOOLS FOR MODELING APPROACHES TO SYSTEMS THINKING IN CHEMISTRY EDUCATION

Holme, T.A.[a], *Apotheker, J.H.*[b], Ho, F.[c], Lavi, R.[d]

A PROGRESS REPORT ON A ROADMAP FOR GREEN CHEMISTRY EDUCATION'

MacKellar, J.M.[a], Holme, T.A [b], Hutchison, J.E.[b]

ADDING SYSTEMS THINKING TO THE ANCHORING CONCEPTS CONTENT MAP

Holme, T.A.[a], *Murphy, K.L.*[b], Raker, J.R.[c]

Constructing opportunities for systems thinking within traditional general chemistry content.

Thomas Holme, Iowa State University (USA)
Peter Mahaffy, Kings University (Canada)

Other STICE Talks/Workshops at ICCE

CONSIDERING EARTH AND SOCIETAL SYSTEMS AS WAYS TO INFUSE SYSTEMS THINKING IN CHEMISTRY EDUCATION

Holme, T.A.[a], *Mahaffy, P.G.*[b], Matlin, S.A.[c], MacKeller, J.[d]

PROMOTING SYSTEMS THINKING IN CHEMISTRY EDUCATION —RELEVANT ASPECTS OF CHEMISTRY TEACHING AND LEARNING

Ho, F.M.[a], Boniface, S.[b], Chiu, M.-H.[c], Holmes, T.A.[d], MacKellar, J.[e], Towns, M.H.[f]

SYSTEMS THINKING IN CHEMISTRY EDUCATION: THE LEARNING CHEMISTRY NODE

Apotheker, J.H.

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  K.J. Ooms, R. Hislop-Hook
- IUPAC CCE for their involvement and support
- IUPAC and IOCD for funding

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