4th Green and Sustainable Chemistry Conference
5-8 May 2019
Dresden, Germany
#greenchem2019

Session 4: 6 May 2019
Sustainable Chemistry in Society (Economy and Education)

Systems thinking, green chemistry and the molecular basis of sustainability

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I O C D

Imperial College London
Institute of Global Health Innovation

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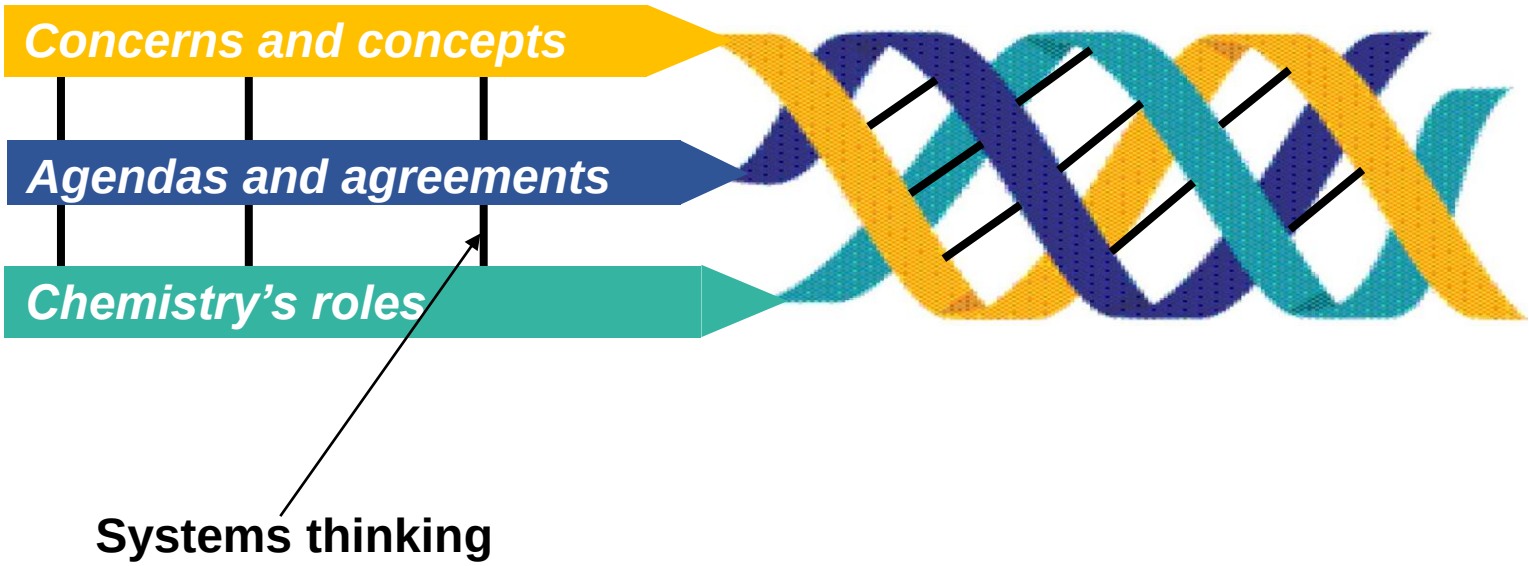
Sustainability



Systems thinking in chemistry
Matlin, Mehta, Hopf, Krief

- *Nature Chemistry* **2015**, *7*, 941-943
- *Nature Chemistry* **2016**, *8*, 393-396

Systems thinking in chemistry education
Mahaffy, Matlin, *et al*

- *Nature Reviews Chemistry* **2018**, *2*, 1-3. http://rdcu.be/J9ep
- *Nature Sustainability* 2019, in press
- *Journal of Chemical Education* 2019, submitted

Sustainability

Chemistry's role

Environmental chemistry

Green chemistry

Life-Cycle Assessment

Sustainability science

One-world chemistry & systems thinking

3Rs logo
USA: Earth Day
22 April 1970

3Rs Initiative: Reduce, Reuse, Recycle

- Makes extensive use of green chemistry & Life Cycle Assessments
- Cradle-to-cradle
- Circular economy
  - breaking the global 'take, make, consume and dispose' pattern of growth
  - private sector: Triple Bottom Line (John Elkington, 1994): social, environmental, financial
  - Zero waste movement
  - Circular chemistry
  - Post-trash

Sustainability

22/04/19

Waste does not exist: there is only post-trash

By: **Henning Hopf, Alain Krief, Goverdhan Mehta, Stephen A. Matlin**

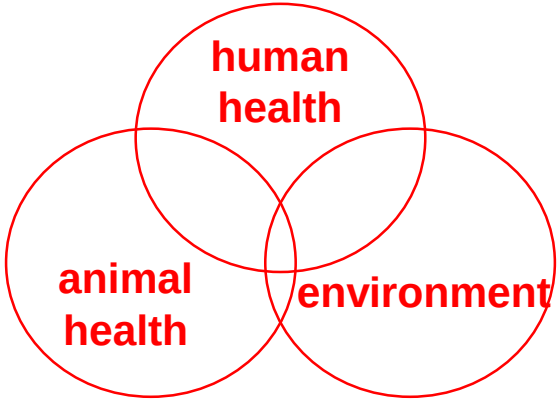
On Earth Day (22 April 2019), it is sobering to recall that the World Bank has estimated that global generation of solid waste currently exceeds 2 billion tonnes per year and will rise by 70 per cent by 2050.

≈

"We need to stop thinking of any materials as being waste and the very concept of waste matter should disappear."

https://www.scidev.net/global/environment/opinion/waste-does-not-exist-there-is-only-post-trash.html

Sustainability



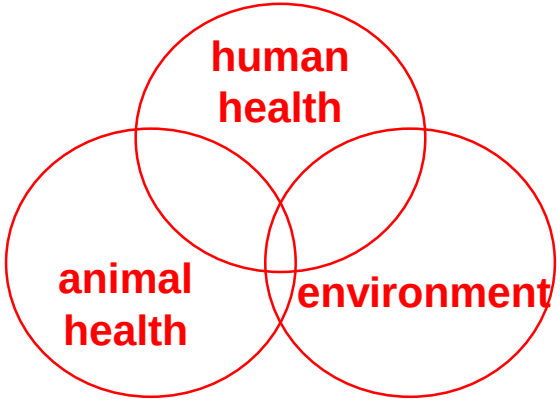
Key linkages in concepts and approaches

- All recognize interdependence between human activity, human and animal health and the biological and physical environments of the planet.
- Prevention, mitigation, clean-up, recycling, etc, require major inputs from chemistry: understanding of the ***molecular basis of sustainability**** and using **systems thinking**❖
  - Green chemistry through **design** –chemists can no longer plead ignorance – they possess ultimate responsibility for consequences in the design.
  - *"By understanding that many of our environmental concerns are derived from molecular characteristics… chemists can realize that many of the solutions are, potentially, also molecular."*

* P. Anastas, J. B. Zimmerman. The Molecular Basis of Sustainability. *Chem* 2016, 1, 10-12

❖ ***Systems thinking can be seen as an interconnecting thread that runs through and unites all these approaches to sustainability***.

Sustainability



Key linkages in concepts and approaches

- All recognize interdependence between human activity, human and animal health and the biological and physical environments of the planet.
- Prevention, mitigation, clean-up, recycling, etc, require major inputs from chemistry: understanding of the ***molecular basis of sustainability**** and using **systems thinking**❖
  - ➢ *"the ways in which the material basis of society and the economy underlie considerations of how present and future generations can live within the limits of the natural world."*
    - central role for chemistry in analyzing, synthesizing, and transforming the material basis of society
    - establishes need for both the practice of chemistry and education in and about chemistry to address sustainability of earth and societal systems.

*P.G. Mahaffy, S.A. Matlin, T.A. Holme, J. MacKellar, *Nature Sustainability*, 2019, in press.

❖ ***Systems thinking can be seen as an interconnecting thread that runs through and unites all these approaches to sustainability***.

International Union of Pure and Applied Chemistry

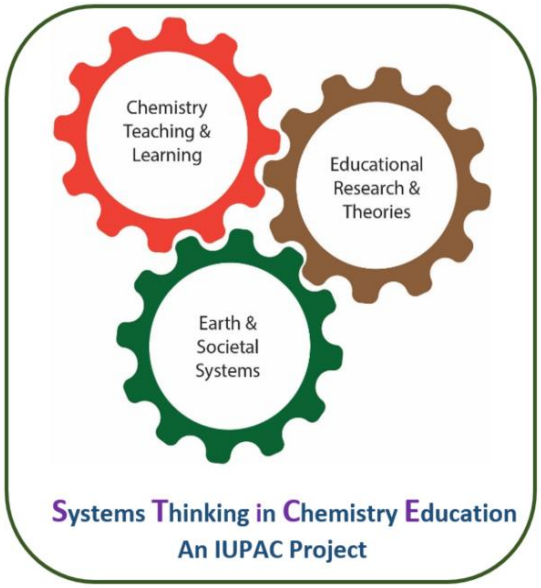
Supported by

International Organization for Chemical Sciences in Development

Infusing Systems Thinking into (Post)-Secondary General Chemistry Education

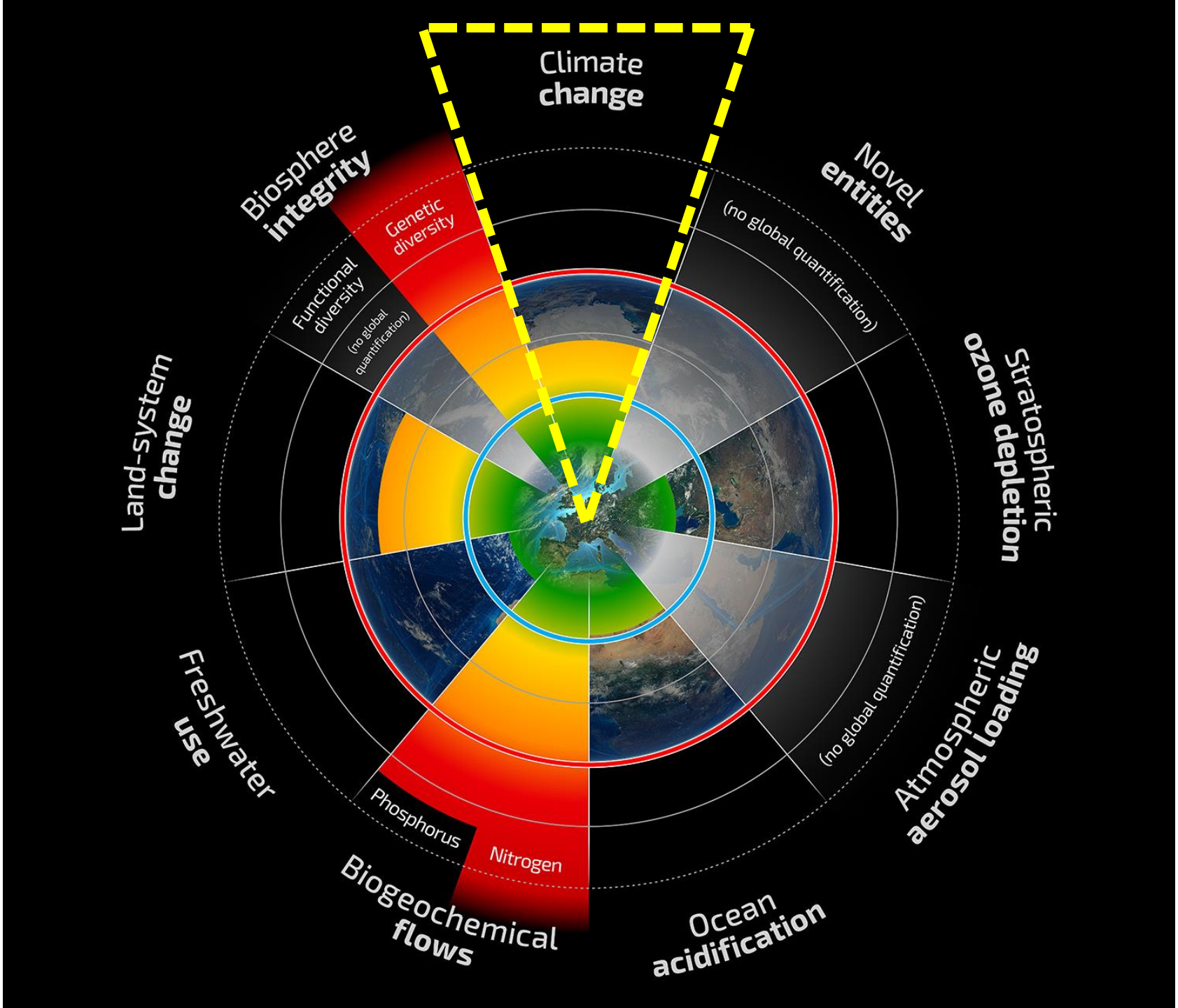
STICE

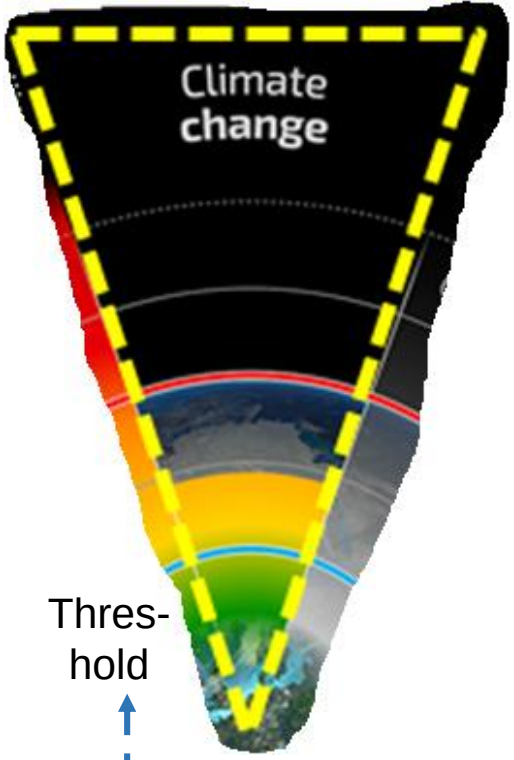
IUPAC Project # 2017-010-1-050



Help students move from fragmented/reductionist knowledge of chemical reactions and processes to a more holistic view, equipping them to be better able to:

- understand chemistry: seeing chemistry itself as an organized system of materials, processes, and products regulated by physical principles
- engage in cross-disciplinary work: seeing how knowledge of chemistry can be leveraged to better understand molecular-level processes in other disciplines
- address emerging global challenges: seeing how chemical processes contribute to and interact with Earth and societal systems to impact planetary sustainability


Climate change
Novel entities
(no global quantification)
Stratospheric ozone depletion
Atmospheric aerosol loading
(no global quantification)
Ocean acidification
Biogeochemical flows
Phosphorus
Nitrogen
Freshwater use
Land-system change
Biosphere integrity
Genetic diversity
Functional diversity
(no global quantification)

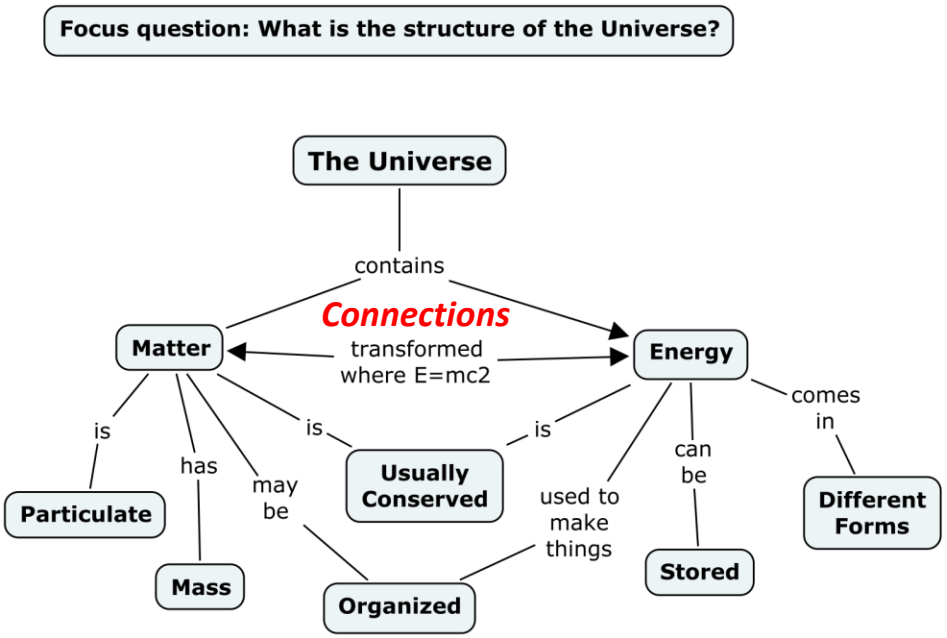


Variable Indicator measured	Below boundary (safe)	In zone of uncertainty	Beyond zone of uncertainty (increasing risk) (High risk)	Planetary boundary	Value of indicator (2015)
Climate change **Atmospheric CO_2 conc^n**				350 ppm	398.5 ppm
Energy imbalance at top of atmosphere				1.0 W / m^2	2.3 W / m^2

Concept map

Concept labels
- **objects**
- **ideas**
- **effects**

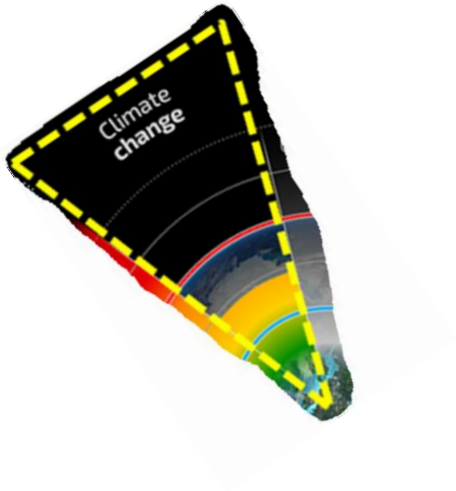
Atoms
Molecules
Heat
Light
Chemical
Electrical
Nuclear
Transformations
Motion
Kinetic energy
Potential energy
Elements
Space
State of Matter
Gases
Liquids
Solids



J.D. Novak, A.J. Cañas. *The Theory Underlying Concept Maps and How to Construct and Use Them*, Technical Report IHMC CmapTools 2006-01 Rev 01-2008, Florida *Institute for Human and Machine Cognition, 2008.* http://cmap.ihmc.us/docs/pdf/TheoryUnderlyingConceptMaps.pdf
http://cmap.ihmc.us/docs/theory-of-concept-maps

Concept map

Biogeochemical flow CO_2



Chemistry of carbon cycle

Incomplete hydrocarbon combustion causes

Atmospheric aerosol loading

Affects

Causes

Metabolism causes

Combustion caused large increase in

Weather patterns and events

Causes

CO_2 in atmosphere

Dissolved CO_2

Affects

Health effects

Increases greenhouse effect: leads to global warming

Ocean acidification

Causes

Affects CO_2 solubility

Causes

Leads to

Climate change

Destroys coral

Alters

Freshwater use

Causes

Causes

Affects

Leads to

Change in biosphere integrity

Biogeochemical flows

Land system change

The most important technological invention of the 20th Century?

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

Haber-Bosch Process

- NH_3 plant produces 1,000-3,000 t/day
- World production 2017 c. 175Mt
- **c. 85% used in agriculture**

Without the N fertilizers spread on the fields, from the Haber-Bosch synthesis of ammonia, 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, *Nature* **1999,** *400*, 415

The most important technological invention of the 20th Century?

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

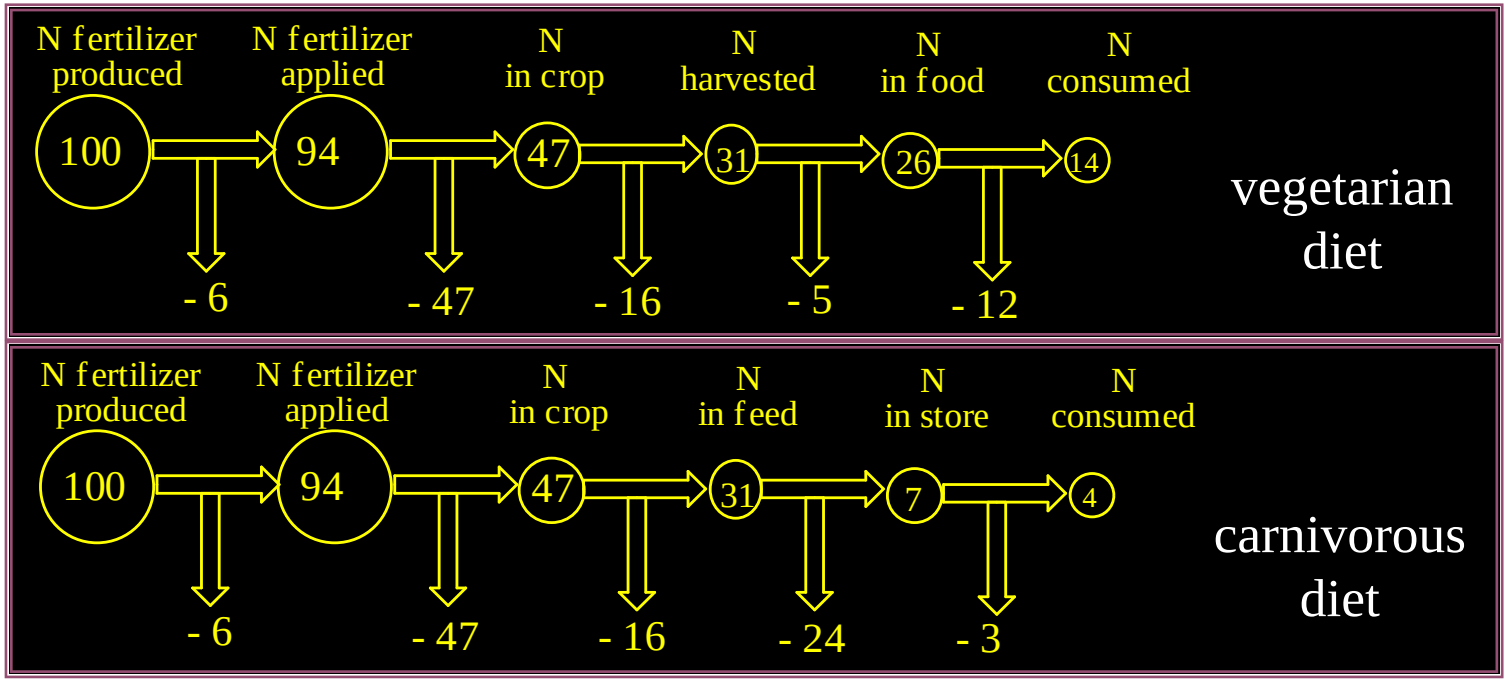
Feeding the world…

…yet, a failure of systems thinking in chemistry?

Making and using N fertilizer

- High demand for energy

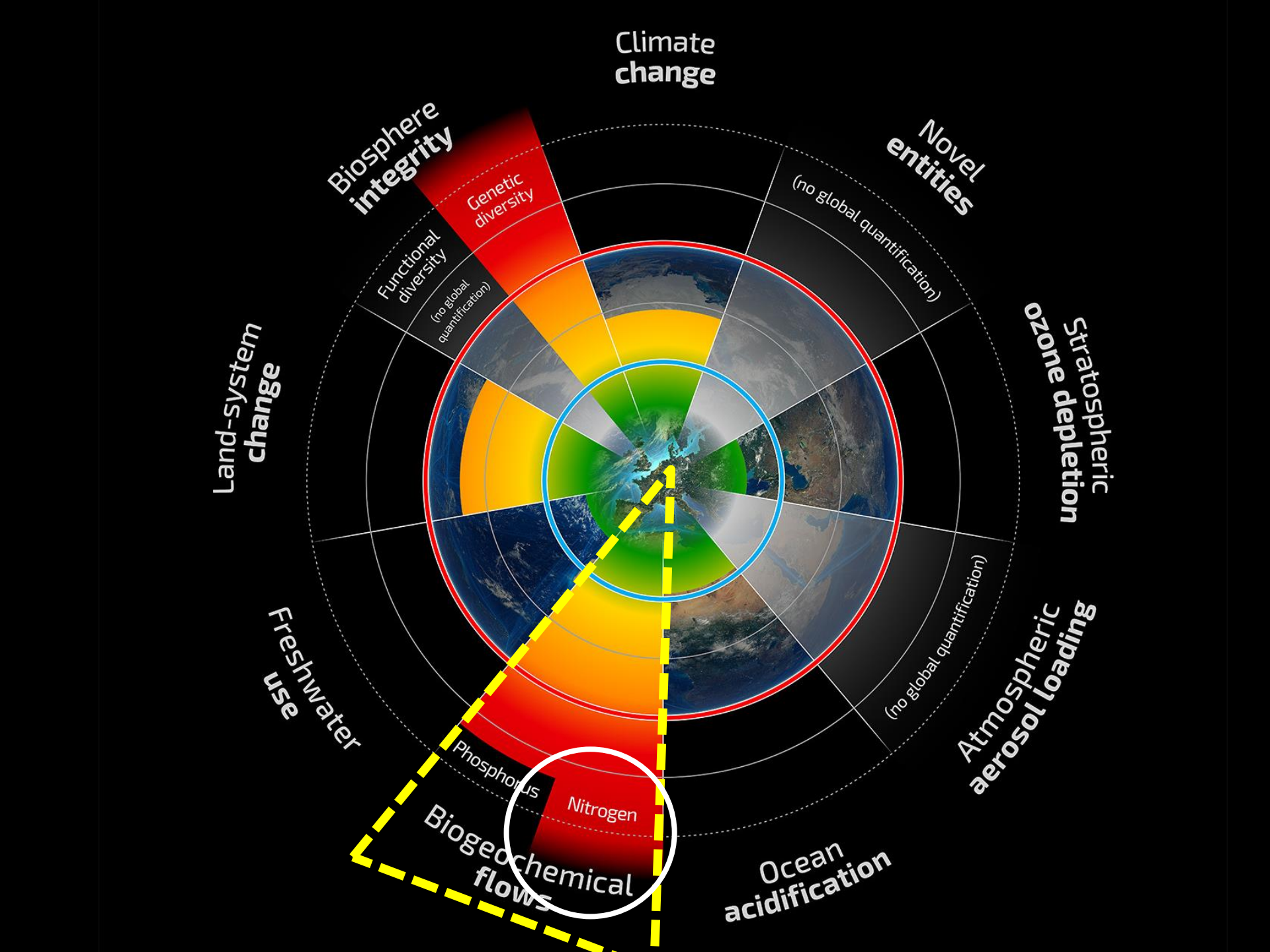
  1.8% of global fossil fuel consumption in 2017
- Wasteful of N



Mahaffy et. al, *Chemistry: Human Activity, Chemical Reactivity*, Nelson/Cengage, 2015

- Damaging to environment

  Air, land, oceans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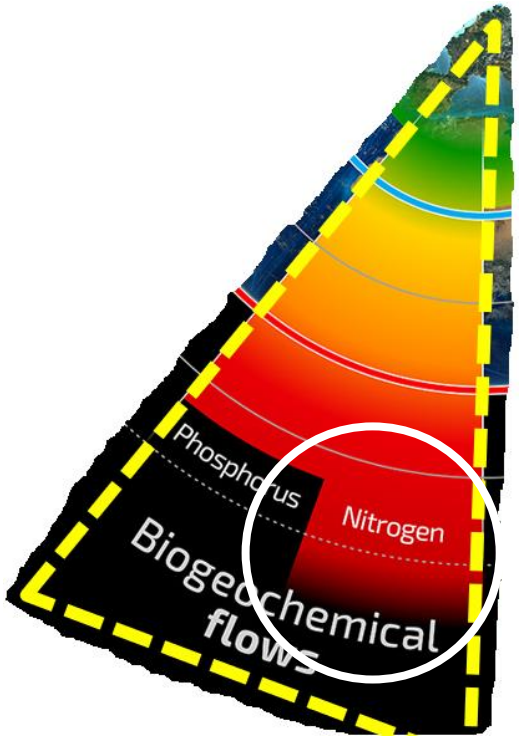
Functional diversity
(no global quantification)
Biosphere integrity
Genetic diversity

Planetary boundary

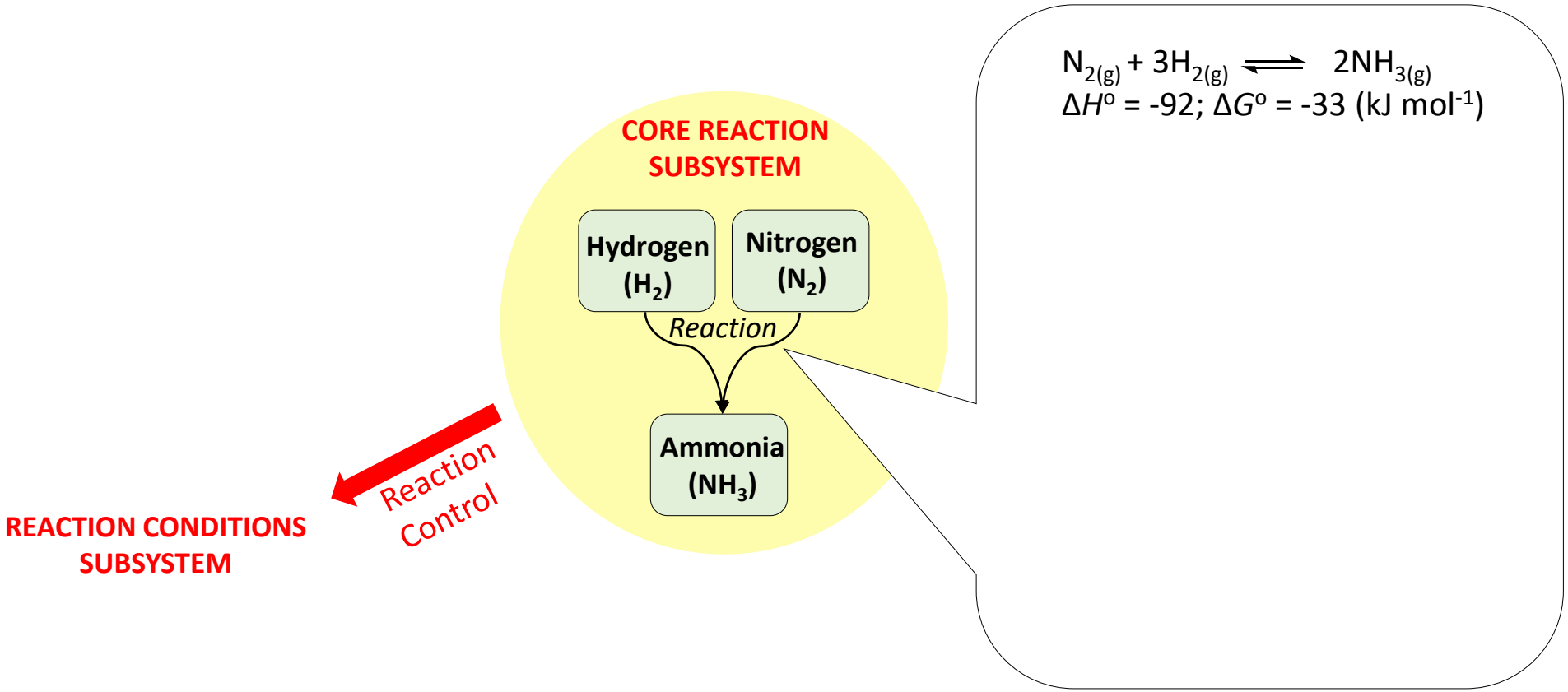
Threshold

Variable Indicator measured	Below boundary (safe)	In zone of uncertainty	Beyond zone of uncertainty (increasing risk) (High risk)	Planetary boundary	Value of indicator (2015)
Biogeochem. flow: N Industrial& intentional biological N fixation				62 Tg / y	150 Tg / y



Reactive N *SOCME*

Systems-oriented concept map extension



Reactive N *SOCME*

ENERGY INPUT SUBSYSTEM

CORE REACTION SUBSYSTEM

Hydrogen (H_2) + **Nitrogen (N_2)** → *Reaction* → **Ammonia (NH_3)**

REACTION CONDITIONS SUBSYSTEM

- **High pressure**
- **Fe-based catalyst**
- **High temperature**

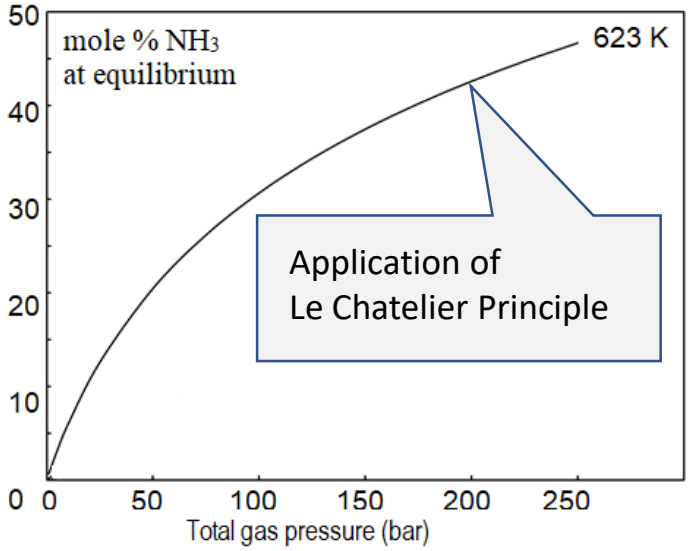
Reaction requires the reaction conditions.

Influence the **Equilibrium**.

Reaction tends towards **Ammonia (NH_3)**.

$N_{2(g)} + 3H_{2(g)} \rightleftharpoons 2NH_{3(g)}$

$\Delta H^o = -92$; $\Delta G^o = -33$ (kJ mol^{-1})



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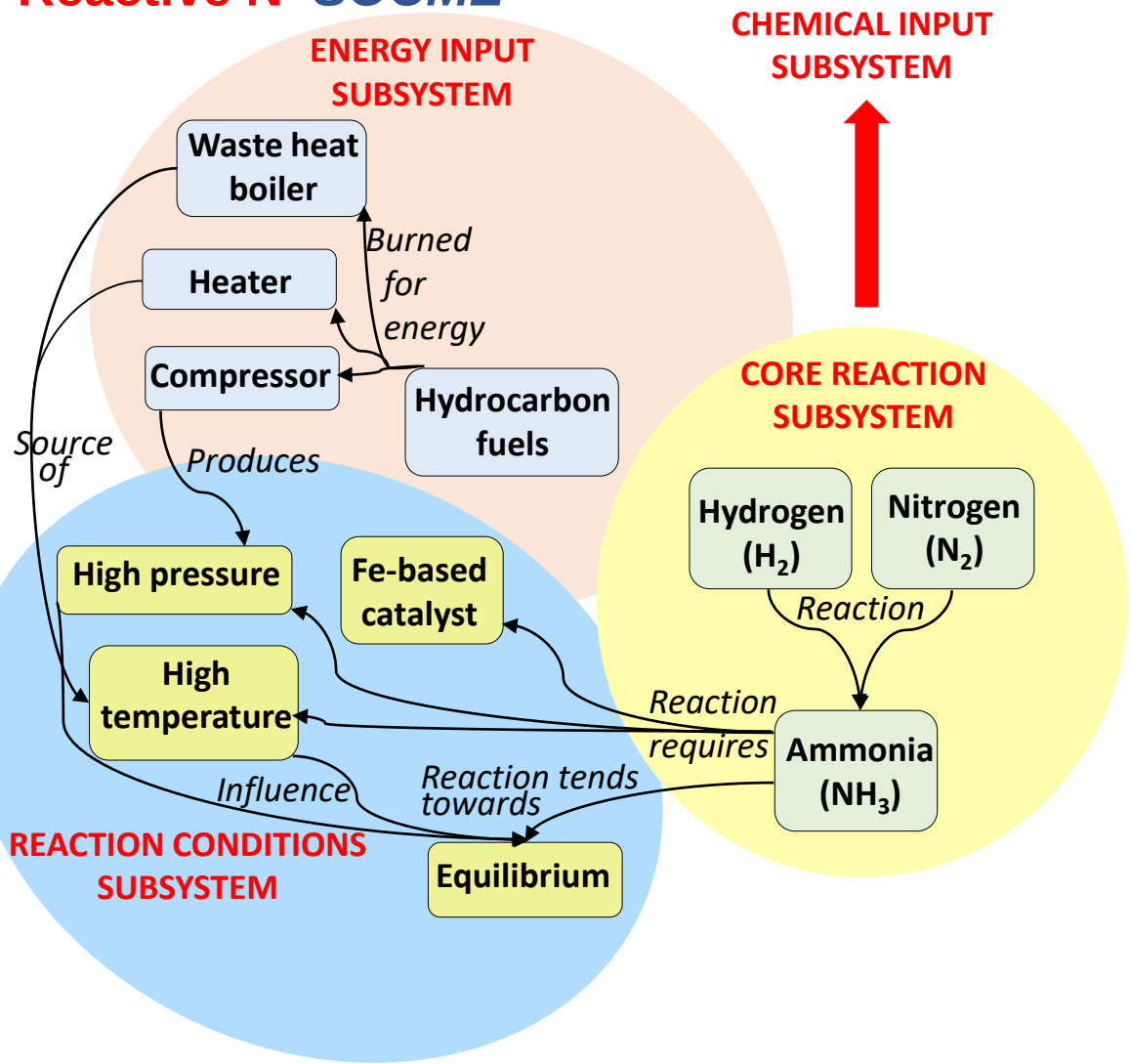

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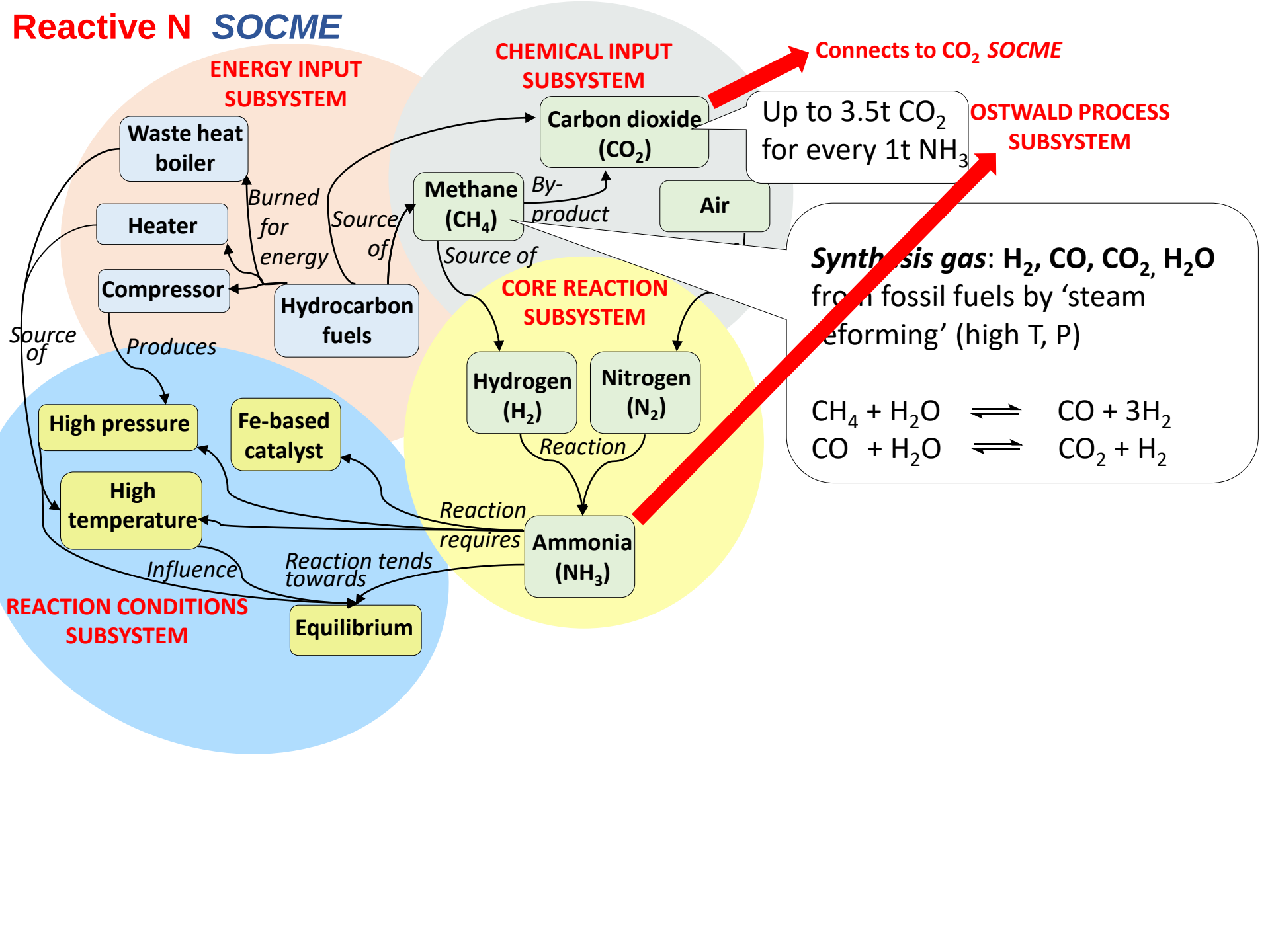
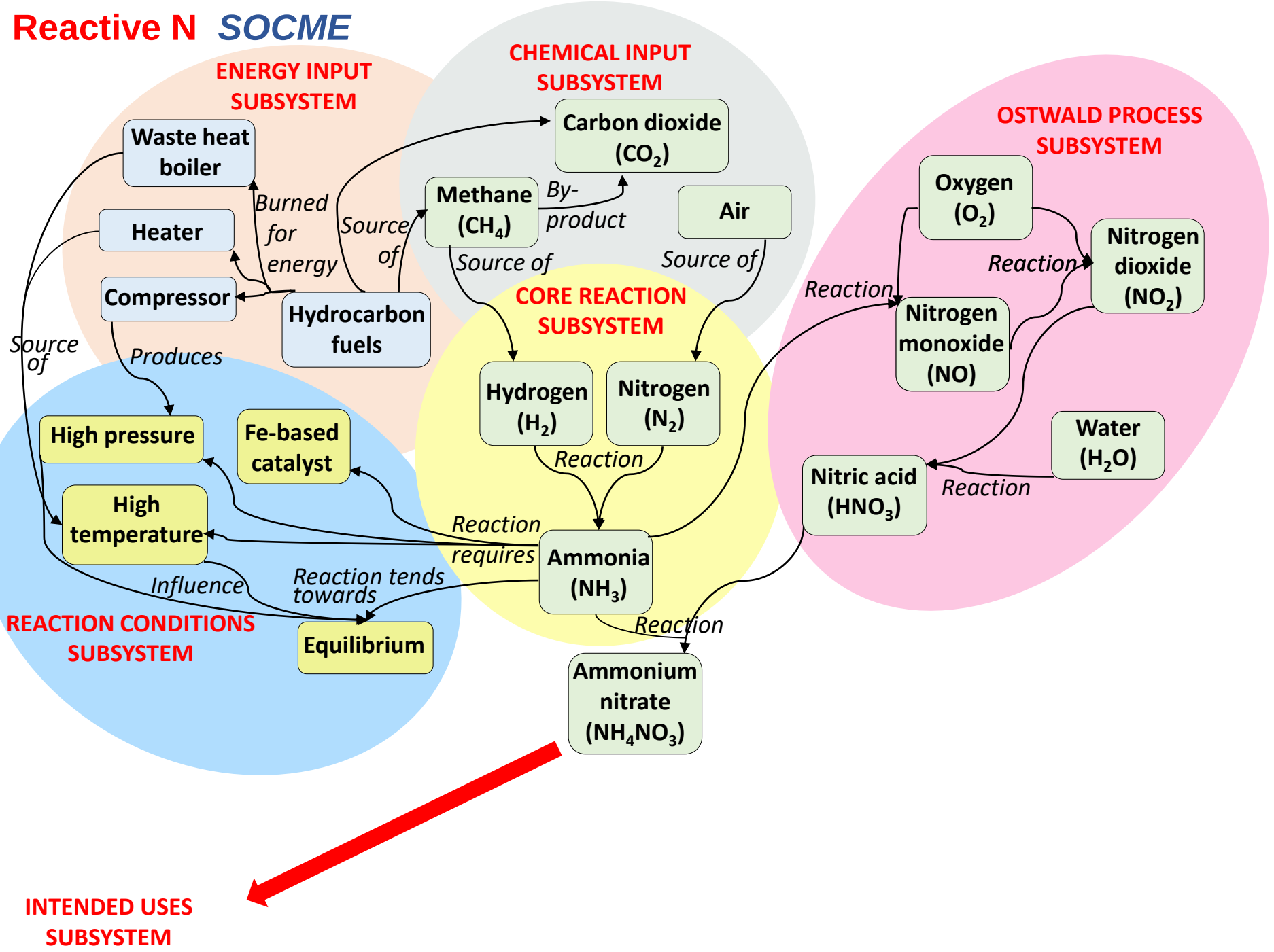
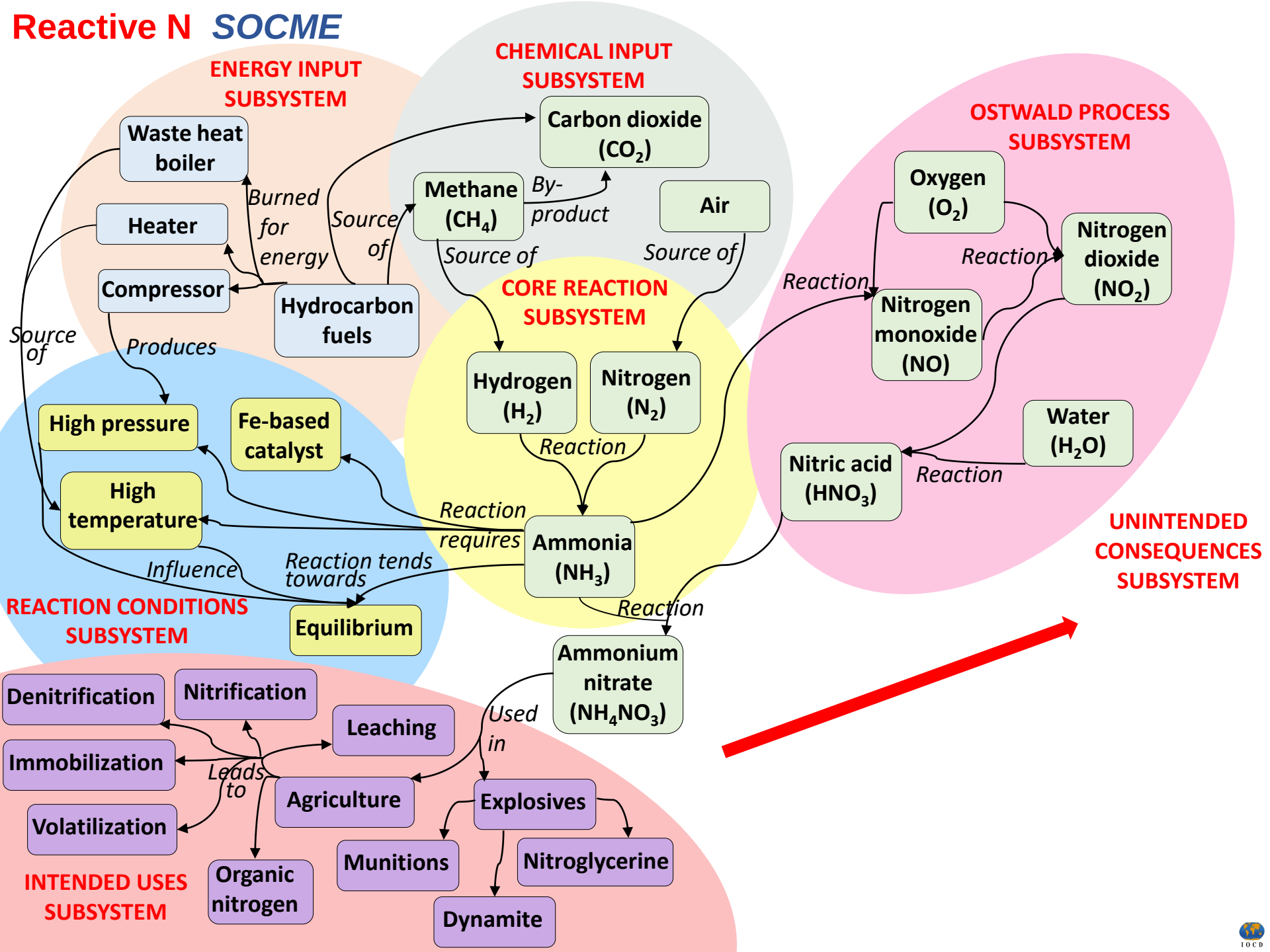



Reactive N SOCME
ENERGY INPUT SUBSYSTEM
CHEMICAL INPUT SUBSYSTEM
OSTWALD PROCESS SUBSYSTEM
CORE REACTION SUBSYSTEM
REACTION CONDITIONS SUBSYSTEM
INTENDED USES SUBSYSTEM
Waste heat boiler
Heater
Compressor
Hydrocarbon fuels
Burned for energy
Source of
Produces
Carbon dioxide (CO_2)
Methane (CH_4)
By-product
Air
Source of
Source of
Oxygen (O_2)
Nitrogen dioxide (NO_2)
Reaction
Reaction
Nitrogen monoxide (NO)
Hydrogen (H_2)
Nitrogen (N_2)
Reaction
Water (H_2O)
Nitric acid (HNO_3)
Reaction
High pressure
Fe-based catalyst
High temperature
Reaction requires
Ammonia (NH_3)
Influence
Reaction tends towards
Equilibrium
Reaction
Ammonium nitrate (NH_4NO_3)

Reactive N *SOCME*



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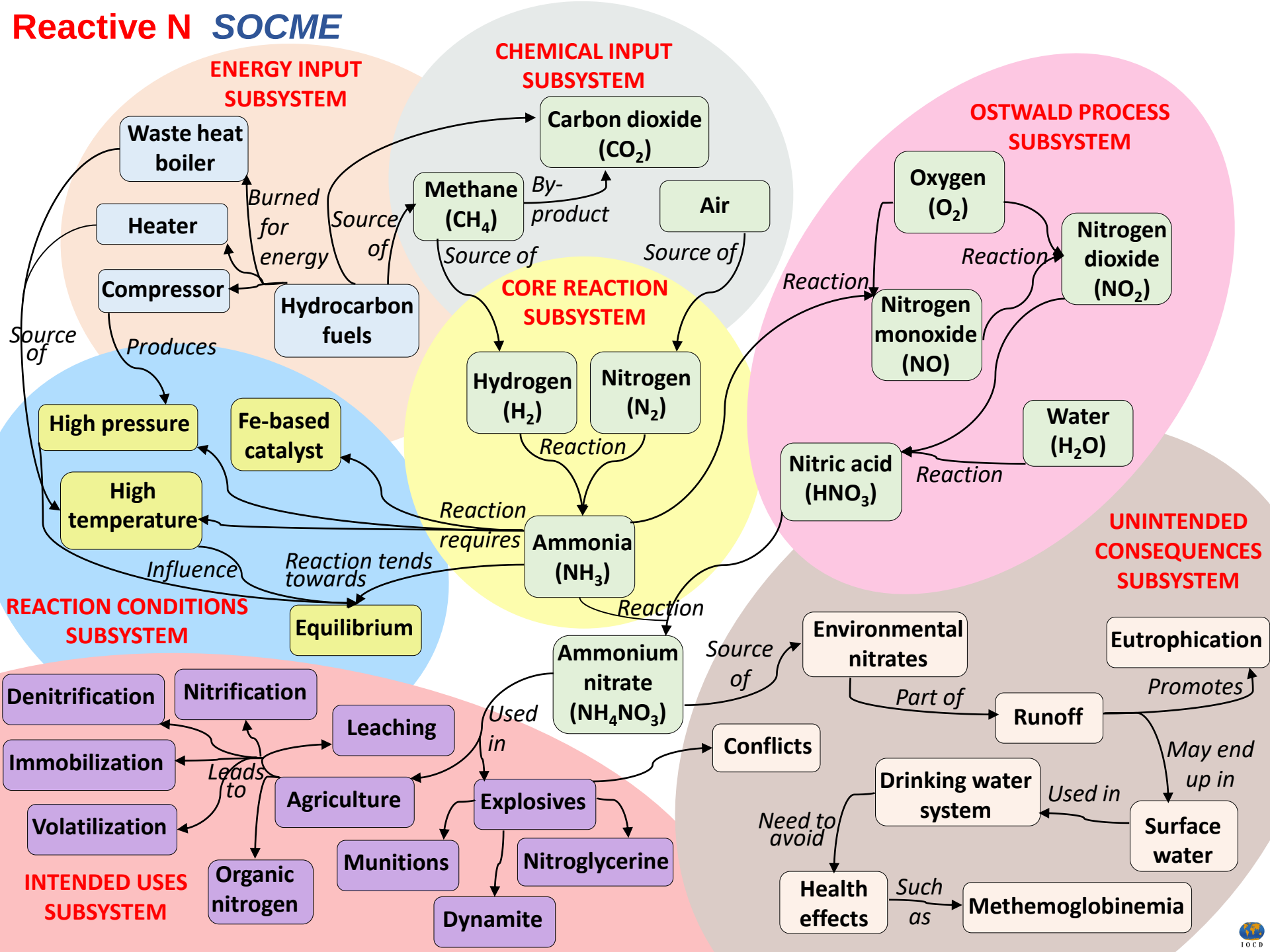

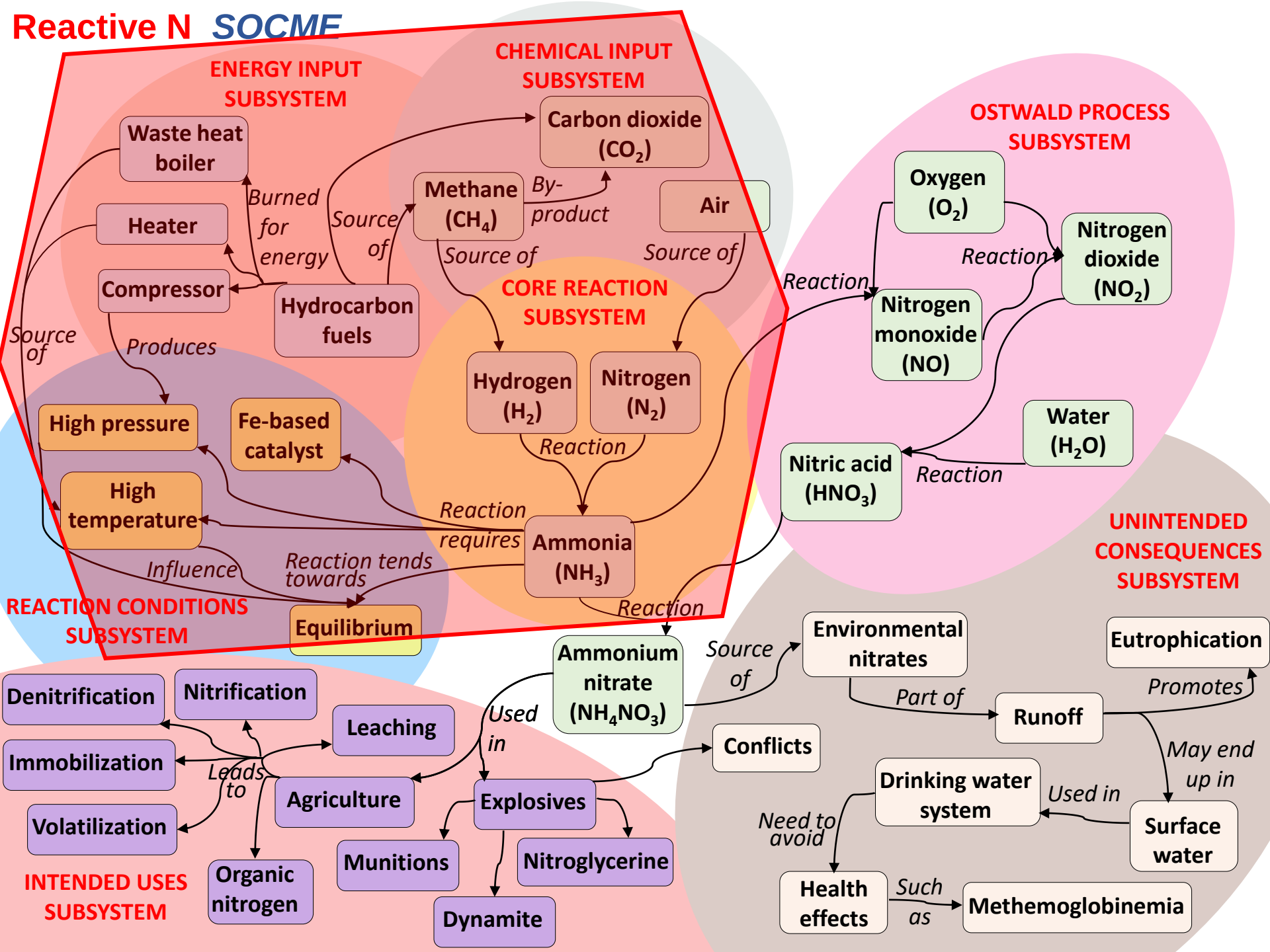
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UNINTENDED CONSEQUENCES SUBSYSTEM
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Waste heat boiler
Heater
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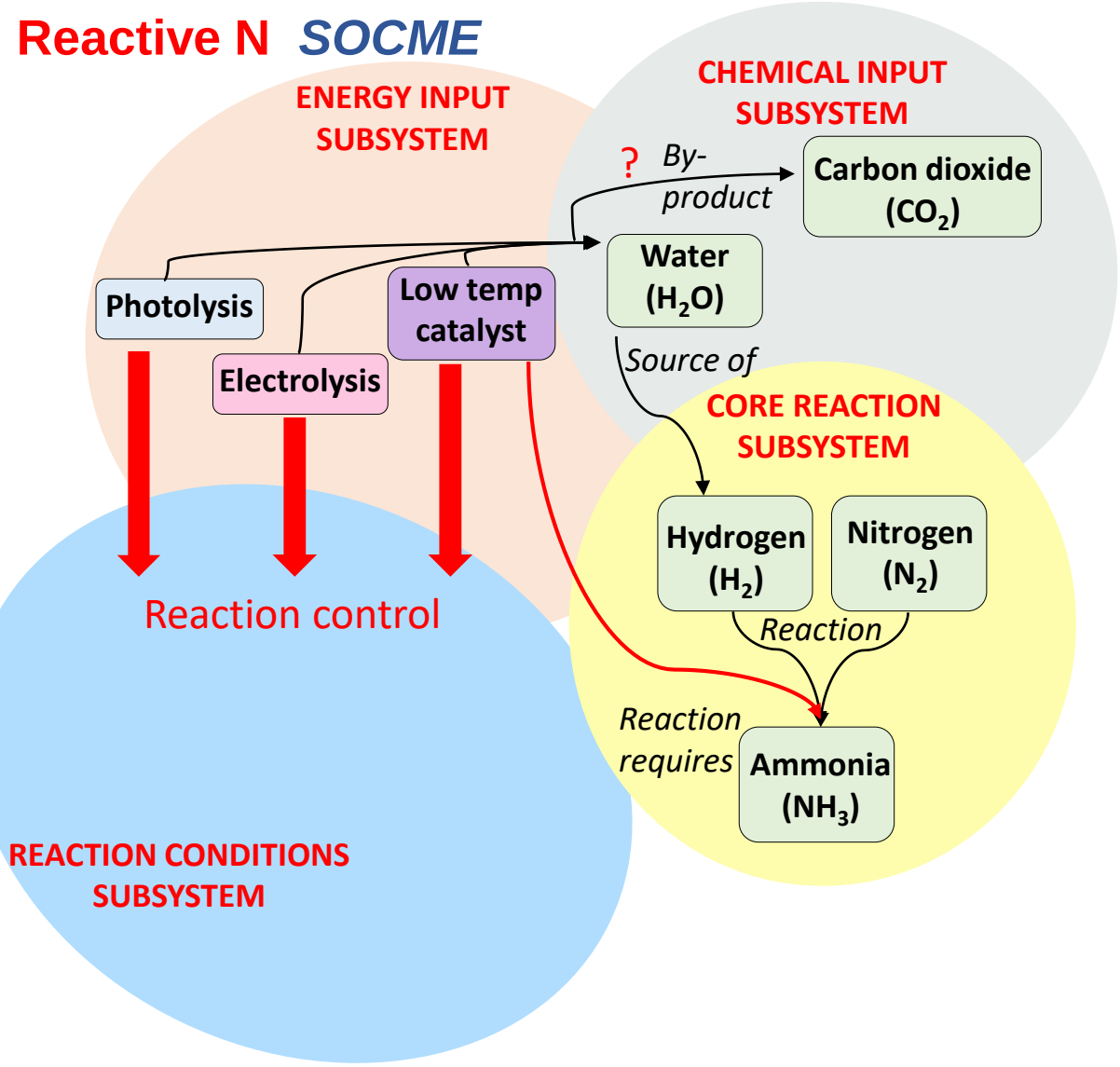
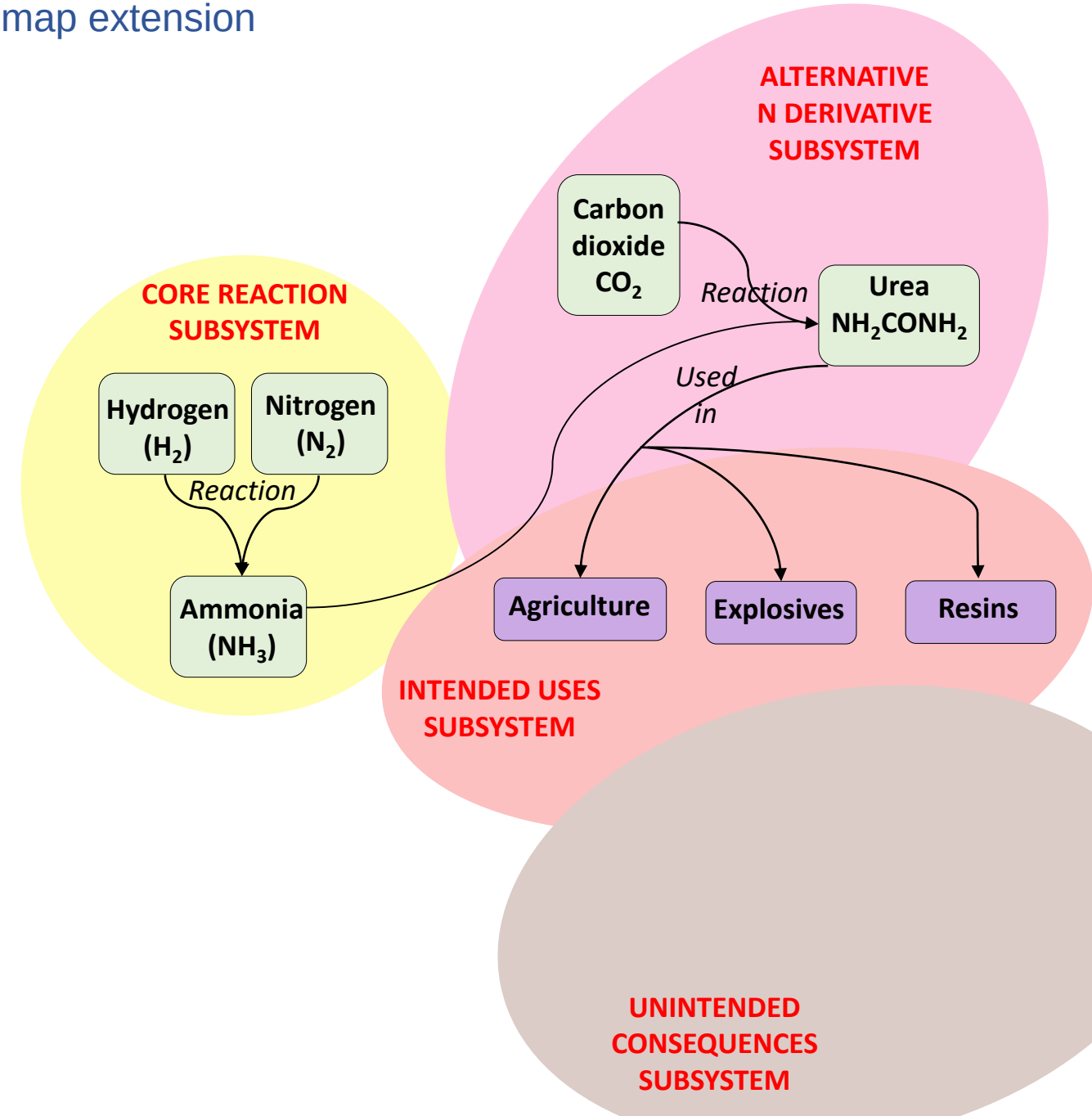
Hydrocarbon fuels
Burned for energy
Source of
Produces
Carbon dioxide (CO_2)
Methane (CH_4)
By-product
Air
Source of
Source of
Hydrogen (H_2)
Nitrogen (N_2)
Reaction
Oxygen (O_2)
Nitrogen dioxide (NO_2)
Reaction
Nitrogen monoxide (NO)
Reaction
Water (H_2O)
Nitric acid (HNO_3)
Reaction
High pressure
Fe-based catalyst
High temperature
Reaction requires
Ammonia (NH_3)
Influence
Reaction tends towards
Equilibrium
Reaction
Ammonium nitrate (NH_4NO_3)
Source of
Environmental nitrates
Part of
Runoff
Promotes
Eutrophication
May end up in
Surface water
Used in
Drinking water system
Need to avoid
Health effects
Such as
Methemoglobinemia
Used in
Conflicts
Explosives
Munitions
Nitroglycerine
Dynamite
Leads to
Agriculture
Denitrification
Nitrification
Leaching
Immobilization
Volatilization
Organic nitrogen

Reactive N *SOCME*



Reactive N *SOCME*

Systems-oriented concept map extension



JOURNAL OF CHEMICAL EDUCATION

News and Announcements

Cite This: J. Chem. Educ. 2018, 95, 1689−1691

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Journal of Chemical Education Call for Papers—Special Issue on Reimagining Chemistry Education: Systems Thinking, and Green and Sustainable Chemistry

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ABSTRACT: The *Journal of Chemical Education* announces a call for papers for an upcoming special issue on Reimagining Chemistry Education: Systems Thinking, and Green and Sustainable Chemistry.

KEYWORDS: *High School/Introductory Chemistry, First-Year Undergraduate/General, Upper-Division Undergraduate, Curriculum, Environmental Chemistry, Interdisciplinary/Multidisciplinary, Problem Solving/Decision Making, Green Chemistry, Learning Theories, Student-Centered Learning, Systems Thinking, Sustainability*

Acknowledgments

- IUPAC Project No 2017-010-1-050 on Systems Thinking In Chemistry Education (STICE) is supported by IUPAC and IOCD
- S.A.M. thanks IOCD for support to participate in this meeting.

Thanks to:

- Tom Holme for leading the development of the SOCME visualization tool
- the entire STICE Steering Group for contributing to the STICE programme

Look out for:

- Special Issue of the Journal of Chemical Education on Reimagining chemistry education: Systems thinking, and green and sustainable chemistry

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